

**Demonstration of LNG Heavy-  
Duty Semi-Tractors  
Equipped with Upgraded  
DDC Series 60G Engines**

**CONSULTANT REPORT**

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Gray Davis, Governor



## **Demonstration of LNG Heavy-Duty Semi-Tractors Equipped with Upgraded DDC Series 60G Engines**

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Commission  
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Effective January 22, 2000, the Transportation Technology group of ARCADIS Geraghty & Miller (ARCADIS) was purchased by Arthur D. Little, Inc. (ADLittle). Thus, work performed by the prime contractor in this project was initiated under ARCADIS and completed under ADLittle. For simplicity, ADLittle is referred to solely as the prime contractor in this report.

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# **1. ABSTRACT / EXECUTIVE SUMMARY**

## **1.1 PROJECT BACKGROUND AND OBJECTIVES**

Among on-road motor vehicles, Diesel-fueled heavy-duty trucks emit disproportionately high amounts of oxides of nitrogen (NO<sub>x</sub>) and particulate matter (PM). The trucking industry has taken an active interest in the use of engines powered by liquefied natural gas (LNG) to reduce NO<sub>x</sub> and PM emissions. However, major barriers exist to widespread use of LNG in trucking applications, including reduced performance and higher initial capital costs compared to diesel-fueled vehicles, as well as a limited fueling infrastructure.

To help address these barriers, the California Energy Commission (Commission) joined with the South Coast Air Quality Management District (SCAQMD) and the U.S. Department of Energy's National Renewable Energy Laboratory (DOE/NREL) in cost sharing a program led by the West Coast Transportation Technology Group<sup>1</sup> of Arthur D. Little, Inc. (ADLittle).<sup>2</sup> The objective of the program was to upgrade three LNG-fueled semi-tractors with new-generation Detroit Diesel Corporation (DDC) Series 60G (S60G) engines that can deliver high horsepower and torque, and demonstrate these LNG tractors in revenue service in a Southern California trucking fleet. A specific goal was to enhance the commercial viability of this low-emission, high-horsepower, high-torque LNG engine for use in Class 8 semi-tractors. Successful commercialization in this high-fuel-use sector can ultimately lead to the displacement of large and significant diesel fuel volumes.

## **1.2 SPONSORSHIP AND PARTICIPANTS**

This project was sponsored under Commission Grant No. MHD-98-001, with extensive cost sharing from other government entities (SCAQMD and DOE/NREL) as well as various industry stakeholders. Table 1-1 provides a quick reference for the three trucks and how funds from the Commission, SCAQMD and DOE/NREL were applied for the each vehicle.

ADLittle served as the prime contractor for the Commission under contract #ACI-6-16627-01. Table 1-2 lists the subcontractors used by ADLittle, and the functions they served in the project.

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<sup>1</sup> This group consists of staff in the Cupertino and Irvine offices in California, and is part of the group formerly known as Acurex Environmental.

<sup>2</sup> On January 22, 2000, ARCADIS Geraghty & Miller's Transportation Technology Group became part of Arthur D. Little, Inc. (see box on page ii).

**Table 1-1. Overview of the JBK LNG truck demonstration (Commission funding shaded)**

LNG Tractor	#1	#2	#3
Primary Funding Agency and Purpose of Funding	NREL: engine upgrade SCAQMD: 12-month demo, field support and data collection, LNG fueling, emissions, reporting	Commission: engine upgrade, 18-month demo, field support and data collection, reporting	Commission: engine upgrade, 18-month demo, field support and data collection, reporting
Secondary Funding Agency	Commission: extension of demo by at least 6 months	SCAQMD: cost-share engine upgrade	SCAQMD: cost-share engine upgrade
Date in Commission-Funded Demo Service	02/09/00	11/2/99	11/2/99

Note: the SCAQMD and DOE/NREL-funded project was fully completed in May 2000

**Table 1-2. Project subcontractors and their roles.**

Subcontractor	Primary Role / Function
Detroit Diesel Corporation (DDC)	Engine and vehicle upgrades, and field support
Valley Detroit Diesel Allison (VDDA)	Subcontractor to DDC, assist with above tasks
Jack B. Kelley, Inc. (JBK)	Vehicle operation, maintenance and data collection

### 1.3 OVERVIEW OF TECHNOLOGY AND PROJECT PARAMETERS

The vehicles selected for this demonstration were 1994 Class 8 Freightliner FLD 120 semi-tractors (see Table 1-3). These were factory-equipped in late 1994 with LNG fuel systems and the first prototype version of the DDC Series 60G. After JBK purchased the three vehicles, DDC and VDDA performed in-chassis engine upgrades, which included modifications to the cylinders and liners as well as the fuel metering, ignition and engine control systems. These modifications were intended to improve the engine's emissions, fuel economy, driveability and reliability, and increase the engine's horsepower from 330 to 400 brake horsepower.

**Table 1-3. Overview of the host site and key demonstration parameters.**

Host Fleet and Location of Operating Base	Jack B. Kelley, Inc. (JBK), Fontana, CA
Chassis	1994 Class 8 Long-Hood Freightliner FLD 120
Engine	LNG-fueled Detroit Diesel Series 60G
Primary LNG Fueling Station Location	Applied LNG Technologies <sup>3</sup> , Ontario, CA
Secondary LNG Fueling Station Location	Mesa Pacific LNG, Downtown Los Angeles, CA
Primary Use Type	Local delivery of cryogenic liquids
Primary Duty Cycle	Short-Haul Stop and Go Delivery
Product Hauled	Cryogenic liquids (principally liquefied nitrogen)

<sup>3</sup> Applied LNG Technologies (ALT) is one of several companies under the umbrella of Jack B. Kelley, Inc. This station is located on the property of United Parcel Services, which is ALT's anchor fleet for both LNG and L/CNG.

## 1.4 WORK PERFORMED AND RESULTS

Most of the objectives for the collective LNG truck program were met or exceeded. Work began in July 1998 under SCAQMD and DOE/NREL funding, when ADLittle negotiated, drafted and executed subcontracts with the host site, Jack B. Kelley (JBK), and the engine manufacturer, DDC. The engine upgrade for LNG Tractor #1 was completed in January 1999, and its demonstration began on February 9, 1999. In late October 1999, the engine upgrades for LNG Tractors #2 and #3 were completed, with initiation of the extended demonstration under Commission funding occurring in November 1999. All three tractors were deployed in the Fontana, California fleet of JBK, where they were primarily used to haul cryogenic liquids throughout Southern California. JBK was charged with gathering data during the demonstration to document fuel consumption, mileage accumulation, road calls, regular maintenance, and oil consumption. Similar data was to be gathered from a diesel truck for comparison. Effective and accurate data collection was significantly hindered by employee turnover at JBK's Fontana depot, however.

### 1.4.1 Mileage Accumulation, Performance and Months of Operation

Over the first nine months of demonstration, LNG Tractor #1 performed extremely well and accumulated approximately 47,000 miles. High engine oil consumption was the only problem documented; the primary cause was found to be a defective oil control ring in the #6 cylinder. By early 2000, all three engine upgrades were complete and JBK was intermittently operating each LNG tractor at its Fontana depot. Figure 1-1 shows the mileage accumulation over time for the three LNG tractors and the diesel control tractor.

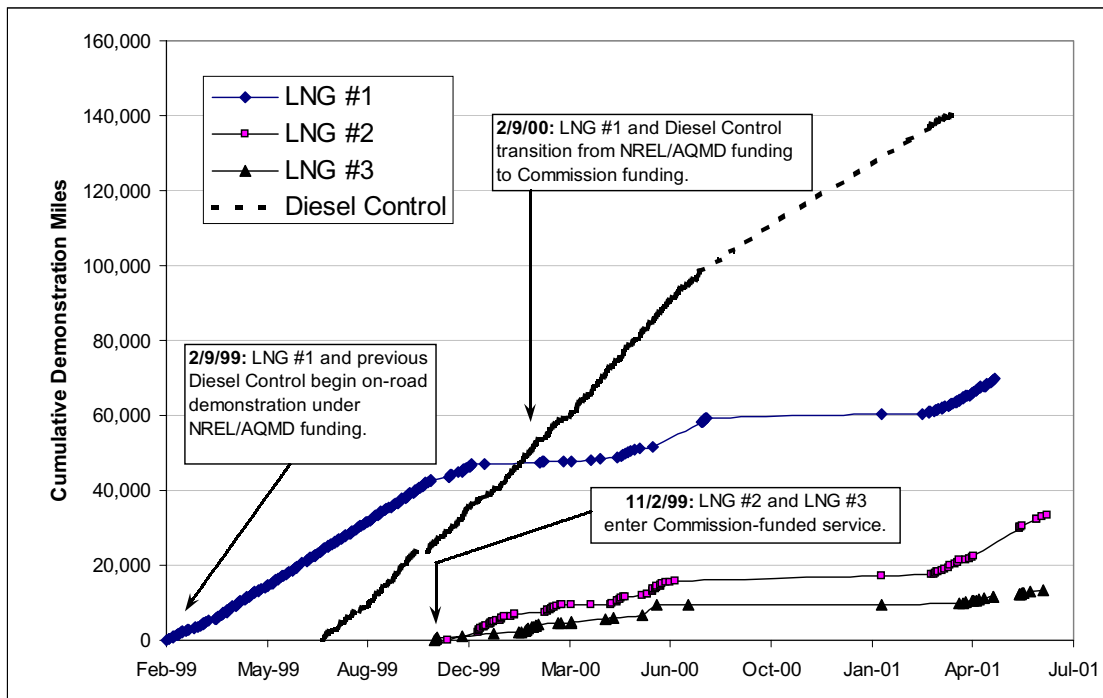


Figure 1-1 . Mileage accumulation for LNG Tractors #1, #2 and #3 vs. diesel control

Mileage accumulation for all three LNG tractors was significantly hindered at times by the need for vehicle and fuel system upgrades. In addition, employee turnover at the depot resulted in downtime for the LNG tractors, due to a lack of available drivers. As a result, LNG Tractors #1, #2, and #3 accumulated only 50%, 24% and 9%, respectively, of the diesel control tractor's mileage. During the course of the Commission-funded demonstration, the tractors were collectively *available* for JBK's use for 38 total months, out of a possible 56 vehicle-operation months.

#### 1.4.2 Fuel Economy and Vehicle Range

The LNG tractors averaged 2.48 miles per LNG gallon over the course of the full demonstration program. On an energy basis, this is equivalent to approximately 4.22 miles per gallon of diesel. Average measured efficiency for the spark-ignited LNG engines was about 27% lower than the control tractor with a comparable DDC Series 60 diesel engine, and about 34% lower than the efficiency of JBK's fleet of diesel tractors with Cummins M11 diesel engines (see Figure 1-2). However, at least some of the measured lower efficiency can be attributed to a less-efficient duty cycle in which the LNG tractors were operated, and unoptimized LNG fueling procedures used in the demonstration. The effective driving range for the LNG tractors was approximately 535 miles – substantially less than the 1,000+ range of comparable diesel tractors.

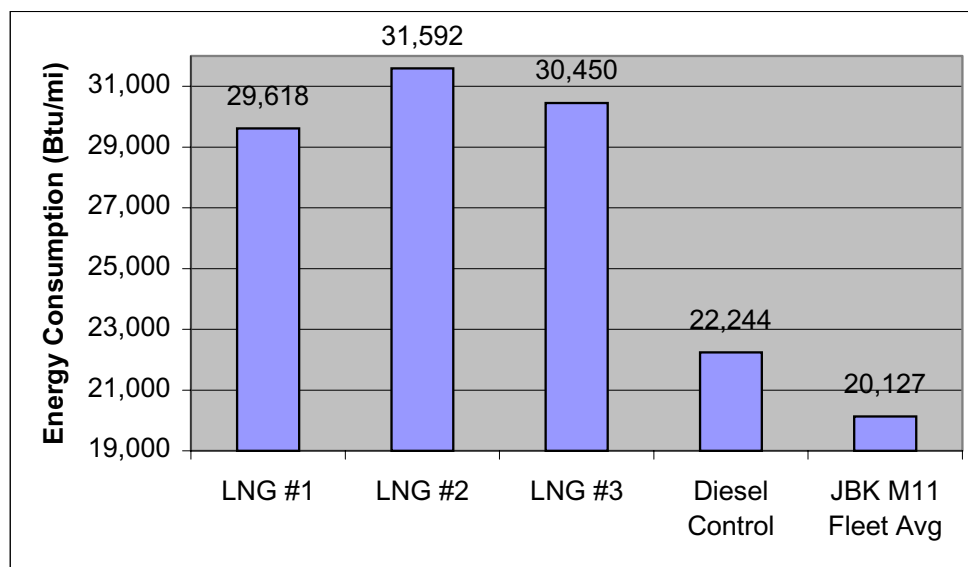


Figure 1-2. Average Energy Consumption for the LNG Tractors vs. Diesel

#### 1.4.3 Engine Certification and Emissions Testing

DDC completed certification of the upgraded 400 hp Series 60G LNG engine in January 2000. Table 1-4 lists the results of certification testing conducted at Southwest Research Institute.

**Table 1-4. Certification emissions testing results at Southwest Research Institute**

Test Cycle	MAX TORQUE (lb-ft)	RATING (hp @ rpm)	NOx (g/bhp-hr)	NMHC (g/bhp-hr)	CO (g/bhp-hr)	PM (g/bhp-hr)
FTP*	1450	400@2100	1.95	0.51	1.79	0.010

\*Federal Test Procedure

In addition, chassis dynamometer emissions testing was performed on one of the three LNG trucks at the Clean Air Truck Testing Services (CaTTS) laboratory in Northern California. This testing was arranged by ADLittle and its team, in conjunction with Pacific Gas & Electric, which paid for the testing under a separate project. Emissions data indicate that the LNG truck emitted very low levels of NOx compared to a recent model year diesel engine (see Table 1-5).

**Table 1-5. Comparison of NOx emissions from diesel and LNG tractors tested at CaTTS over the Central Business District (CBD) Test Cycle**

Test Vehicle	Engine / Fuel	Test Fuel	NOx (g/mile)
1986 GMC	'97 DDC Series 50	Diesel #2	27.4
1995 Freightliner FLD 120 (LNG Tractor #3)	Upgraded '95 DDC S60G	LNG	7.2
Testing for the LNG tractor was conducted at CaTTS on April 10, 2000. Testing for the diesel tractor was conducted at CaTTS on March 17, 1999. Certain test parameters (e.g., inertia mass, road load) and vehicle details were not available. NOx data are the average of 3 tests for both vehicles. Particulate data were not available.			

## 1.5 CONCLUSIONS AND RECOMMENDATIONS

Most of the objectives and goals for this project were successfully met, and some were exceeded. Important accomplishments for the project included the following:

- This demonstration marked the first use in California of dedicated natural gas trucks with the high horsepower and torque needed to compete in Class 8 trucking applications. It was an essential step towards full commercialization of dedicated LNG tractors with upgraded, low-NOx DDC Series 60G engines. The funds provided by the Commission, as well as cost sharing from SCAQMD and DOE/NREL, were essential to this achievement.
- Collectively over the course of the two related projects (February 1999 to July 2001), the three LNG tractors accumulated nearly 116,000 miles and consumed approximately 47,000 gallons of LNG. Thus, an estimated 27,500 gallons of diesel fuel were displaced. While these represent relatively small fuel quantities, the near-term potential for greater displacement of diesel fuel in California has been significantly enhanced, due to improved commercial viability of LNG engines in the high-fuel-use Class 8 trucking sector.
- Emissions certification testing on the upgraded Series 60G engine – as well as chassis dynamometer emissions testing of the LNG tractor at CaTTS – have further corroborated

that heavy-duty LNG engines offer major NOx emissions reductions compared to equivalent diesel engines. It is conservatively estimated that the project resulted in about 2.5 tons of reduced NOx emissions in the South Coast Air Basin, through deployment of the three LNG tractors instead of comparable diesel tractors over the 116,000 collective miles of demonstration.

- DDC's certification of the upgraded S60G LNG engine to California's Optional Low-NOx Emissions Credit Standards at 400 hp and 1450 lbs-ft of torque is a significant (if not major) accomplishment. Strong commercial demand is anticipated for this engine, and a significant increase in deployment of heavy-duty LNG trucks may soon follow. In January 2002, the engine was finally acknowledged on the Air Resources Board website as being certified to these special low-NOx emission standards. This will enable fleets purchasing S60G-equipped heavy-duty trucks to obtain funding from the State that offsets the incremental cost of the LNG option over a comparable diesel-powered truck.
- Based largely on knowledge and experience gained in this program, DDC is now deploying at least 32 new LNG tractors in the Southern California fleets of two major grocery chains, Vons Groceries and Albertson's, Inc. These tractors are equipped with the same high-horsepower, high-torque S60G engine developed and demonstrated under the Commission / SCAQMD / DOE-NREL program.

Important "lessons learned" and recommendations derived from this project include the following:

- Much greater numbers of LNG vehicles on the road are needed to make LNG stations and technologies profitable for private industry. Low station density remains a major barrier to wider deployment of LNG vehicles in Class 8 trucking applications. Although new LNG stations came online in California during the term of this demonstration program, accelerated expansion of the infrastructure will be needed to ensure commercial viability. Unlike refuse haulers and transit buses, long-haul trucks do not return to the same location each night for refueling, and thus must rely on the availability of fuel en route. Deployment of LNG buses and refuse haulers will help increase the demand and reduce the costs for additional LNG stations.
- Additional work is clearly needed to improve the engine efficiency and fuel economy of spark-ignited, heavy-duty natural gas engines such as the S60G. Work of this nature is already underway or planned, through other government-funded programs such as those being currently co-funded by the Commission. However, the lower measured fuel economy of the LNG tractors can be partially attributed to certain non-optimal characteristics of the demonstration. Most notably, the LNG tractors were used in a less-efficient duty cycle (local, short-haul service), and fuel-related procedures were conducive to high LNG boil off as well as excess venting losses.
- Running out of fuel, which usually results in a road call and towing, remains a significant problem for LNG trucks. In addition to the paucity of LNG stations, the following other factors contribute to this problem: reduced vehicle range due to lower volumetric energy content of LNG; less accurate fuel gauges; a lack of extensive driver experience with LNG;

the difficulty of getting cold fuel into relatively hot tanks with high vapor pressure; and the not-uncommon need to vent and service an LNG truck's onboard fuel system at a location remote from the nearest fueling station. Some of these issues require technical solutions (e.g., improved and larger on-board LNG storage tanks), while others involve institutional remedies (e.g., improved training of end users).

## 2. INTRODUCTION

### 2.1 PROJECT BACKGROUND AND OBJECTIVES

Diesel-fueled heavy-duty trucks represent a small percentage of the vehicle population in California, but they are major emitters of oxides of nitrogen (NO<sub>x</sub>) as well as fine particulate matter (PM). In addition, heavy-duty trucks use very large quantities of diesel fuel, and are therefore partially responsible for California's near-total dependence on petroleum fuels in the transportation sector. For decades, the California Energy Commission (the Commission) has spearheaded efforts to displace use of diesel with cleaner-burning alternative fuels that can help diversify energy use in the transportation sector. This is a very challenging task, however; the trucking industry heavily relies on heavy-duty diesel engines due to their relative low cost and durable, reliable and efficient operation. Consequently, the trucking industry has been reluctant to use alternative fuels and engines, which have been associated with higher costs, compromised performance, a limited fueling infrastructure, and poorer durability and fuel efficiency.

Despite these current drawbacks, the trucking industry has increasingly taken an active interest in alternative fuels and engines as a means to reduce harmful emissions and enhance energy diversification in the transportation sector. One of the most promising alternative fuels of interest to heavy-duty trucking fleets is liquefied natural gas (LNG). Engines powered by LNG look especially attractive in Class 8 (>33,000-lb Gross Vehicle Weight) short-haul truck applications where large quantities of fuel are used, vehicles are centrally fueled, and routes contain multiple starts and stops. In the mid 1990s, the Commission and other government agencies such as the South Coast Air Quality Management District (SCAQMD) and the Department of Energy (DOE) joined with the major manufacturers of heavy-duty engines and vehicles to accelerate the pace towards developing, demonstrating, and commercializing LNG technologies for heavy-duty trucking applications.

A significant shortcoming in the commercial viability of alternative fuels like LNG for Class 8 trucking applications has been the lack of available engines offering diesel-equivalent horsepower and torque. In late 1997, Arthur D. Little<sup>4</sup> (ADLittle), Detroit Diesel Corporation and Jack B. Kelley, Inc. (JBK) conceived a project to develop and demonstrate a high horsepower, high torque LNG engine based on earlier generations of the DDC Series 60G natural gas engine. Government cost sharing was sought from the Commission, SCAQMD and DOE's affiliate, the National Renewable Energy Laboratory (DOE/NREL). In mid 1998, a first phase of the project was initiated under SCAQMD and DOE/NREL funding, until funding from the Commission also became available. This SCAQMD- and DOE/NREL-funded effort included the following key objectives:

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<sup>4</sup> On January 22, 2000, ARCADIS Geraghty & Miller's Transportation Technology Group became part of Arthur D. Little, Inc. (see box on page ii).

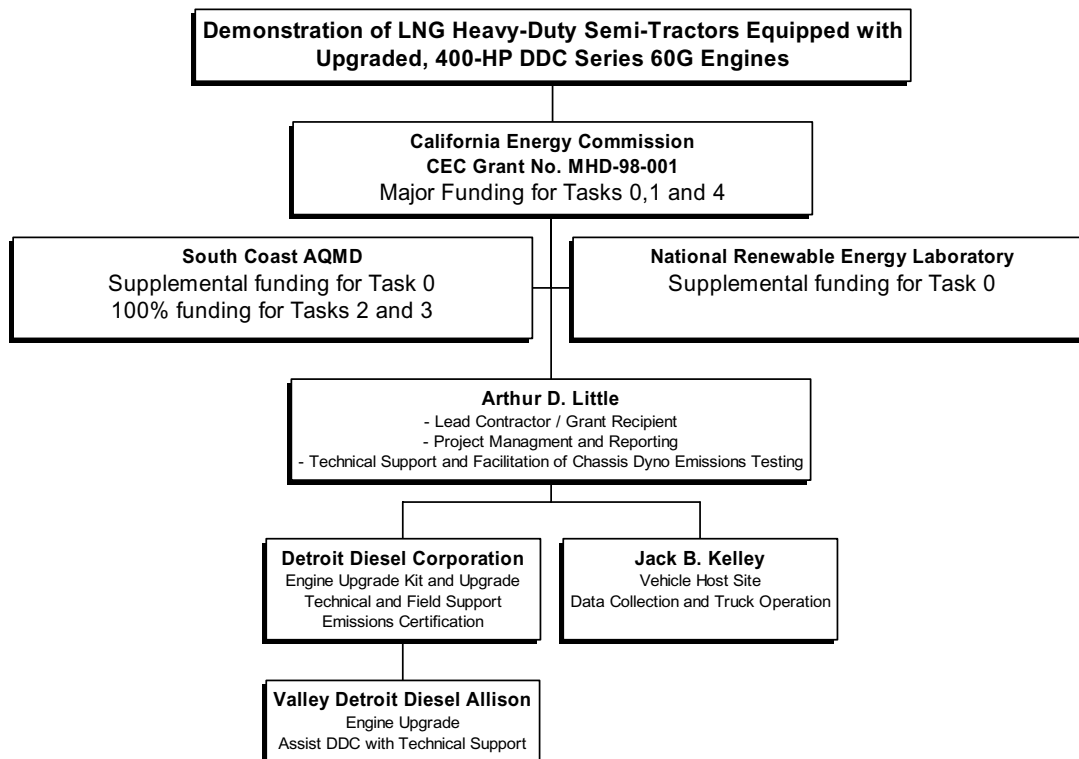
- Purchase one existing Freightliner LNG tractor with the obsolete, first-generation DDC 60G engine
- Upgrade this first Series 60G engine to 400 HP and 1450 lbs.-ft. of torque
- Operate the first LNG tractor in JBK's Southern California fleet for approximately 12 months in revenue service, hauling up to the full 80,000 lbs. GVWR, and document the performance compared to a tractor with a similar diesel engine
- Achieve California certification of the 330 horsepower DDC S60G engine for over-the-road LNG coach applications, and initiate efforts to certify the 400 HP version for trucking applications
- Facilitate chassis dynamometer emissions testing on the LNG tractor (under outside funding as a project cost share)
- Extend the period of operation for the downtown Los Angeles LNG fueling station for approximately one year, through direct financial support

Contracts for the above project were completed in July 1998, and (as further described) the first LNG tractor began demonstration in February 1999. By August 1999, the Commission's funding for a complementary, closely aligned project become available through award of grant contract #MHD-98-001. Essentially this project expanded, extended and augmented the SCAQMD- and DOE/NREL-funded project, by deploying two additional LNG tractors and continuing the demonstration of the first tractor beyond one year. Specific objectives above and beyond the SCAQMD-and DOE/NREL-funded project included the following:

- Purchase two additional existing Freightliner LNG tractors with the obsolete DDC Series 60G engine
- Perform the same engine upgrade (400 HP and 1450 lbs.-ft. of torque) as the first LNG tractor
- Operate these 2<sup>nd</sup> and 3<sup>rd</sup> LNG tractors for approximately 18 months in revenue service at JBK's Southern California fleet
- Extend the demonstration of the 1<sup>st</sup> LNG tractor by at least 6 months.
- Displace the JBK fleet's consumption of diesel fuel (as much as possible)
- Document the performance compared to conventional diesel technology
- Prepare a comprehensive Final Report for all three LNG tractors

## **2.2 PROJECT ORGANIZATION**

As prime contractor to the Commission as well as SCAQMD and DOE/NREL in the two related projects, ADLittle provided comprehensive technical and financial oversight. Figure 2-1 displays the project's organizational and contractual structure, including relationship to the initial effort funded by SCAQMD and DOE/NREL.



**Figure 2-1. Project Organizational Structure**

## 2.3 HISTORY OF PROJECT'S DEVELOPMENT

The three LNG vehicles that were the primary focus of the two combined projects were part of five heavy-duty tractors originally ordered by Ruan truck leasing, and leased by Liquid Carbonic, Inc. (LCI). These were the first tractors to be factory-equipped with an early version of the prototype LNG-fueled DDC Series 60G. LCI planned to dedicate the five trucks to hauling LNG from a new liquefaction plant in Willis, Texas, to LNG customers in the Gulf Coast. The key customer for this planned business was Houston Metro Transit, which had made an early commitment to convert its transit bus fleet to LNG. However, various technical problems with the LNG engines and fuel systems used by Houston Metro led the agency to delay, and ultimately, reverse its LNG conversion plan. As a result, only one of the five tractors was used significantly while leased to LCI.

In January 1996, LCI was sold to Praxair, which subsequently dissolved LCI's LNG business. The five LNG tractors were not operated while Praxair owned them, and they were offered for sale. Meanwhile, DDC had made significant improvements to the S60G engine, increasing its rated power and peak torque to 400-HP @ 2100 rpm and 1450 lbs-ft @ 1200 rpm, respectively. This type of performance was sufficient to meet the demands of the heavy-duty trucking industry,

and DDC was demonstrating a single Class 8 truck powered by the prototype engine in Mobile, Alabama.

JBK was among the first commercial trucking operations to consider using LNG tractors, but at the time there were no commercially available tractors offering diesel equivalent horsepower and torque.<sup>5</sup> Thus, JBK chief executive officer Ken Kelley was interested in demonstrating LNG tractors with the prototype, 400-HP DDC S60G configuration. Kelley agreed to purchase three of the five tractors if government funding could be obtained and DDC could perform the same upgrade to their original S60G engines. ADLittle developed the project further, and obtained funding first from SCAQMD, DOE/NREL, and then the Commission, to upgrade and demonstrate the three LNG tractors.

The SCAQMD / DOE NREL project began in July 1998 when JBK arranged for the first LNG tractor to be towed from Texas to Valley Detroit Diesel Allison, in the City of Industry, California. This tractor was listed in the JBK fleet as #952268. For simplicity in reporting project results, it was designated as “Tractor #1.” As is described further in subsequent sections, “Tractor #2” and “Tractor #3” would subsequently be deployed with Tractor #1 in the JBK fleet, once the project funded by the Commission came on line several months later. Table 2-1 provides details about each of these three tractors, how the various funding dollars were allocated, and the relationship of the two projects (i.e., the original project funded by SCAQMD/DOE/NREL and the follow-on effort primarily funded by the Commission).

**Table 2-1. Overview of funding sources for each of the three demonstration LNG tractors.**

LNG Demo Tractor #	#1 (JBK # 952268)	#2 (JBK #952269)	#3 (JBK #952270)
VIN Number	2FU5DZYB0SA424962	2FU5DZYB6SA424965	2FU5DZYBBSA424966
Odometer at Engine Upgrade	28,720	4,392	3,183
Date in Demo Service	02/09/99	11/2/99	11/2/99
SCAQMD Funding	<ul style="list-style-type: none"> <li>• Technical, field, fueling and emissions testing support</li> <li>• 12-month demo</li> <li>• Differential costs for LNG tractor</li> </ul>	<ul style="list-style-type: none"> <li>• Minor cost share of engine upgrade</li> </ul>	<ul style="list-style-type: none"> <li>• Minor cost share of engine upgrade</li> </ul>
DOE/NREL Funding	<ul style="list-style-type: none"> <li>• Engine upgrade and cost-share of DDC field support</li> </ul>	None	None
Commission Funding	<ul style="list-style-type: none"> <li>• ~6 month demo (extension of AQMD-funded 12 month demo)</li> </ul>	<ul style="list-style-type: none"> <li>• Major cost share of engine upgrade</li> <li>• Technical and field support</li> <li>• ~18-month demo</li> </ul>	<ul style="list-style-type: none"> <li>• Major cost share of engine upgrade</li> <li>• Technical and field support</li> <li>• ~18-month demo</li> </ul>

NOTE: Bold, shaded areas provide a quick view of activities under the Commission-funded program (i.e., the primary subject of this report). Unshaded areas refer to activities primarily funded under the related SCAQMD/DOE/NREL project.

<sup>5</sup> In 1995, JBK ordered up to 10 Kenworth T800 LNG tractors with the 300-HP Cummins L-10 natural gas engine. However, the L10G's horsepower and torque proved to be insufficient for JBK's intended application, resulting in a downscaled demonstration.

### 3. WORK PERFORMED AND RESULTS, BY TASK

This section primarily describes the work performed under Commission funding for each task and the results obtained. Also included (for a complete picture of the full project) are descriptions of work performed and results obtained under funding from the SCAQMD and DOE/NREL.

#### 3.1 TASK 0 — Engine Upgrades

The upgrades to three Series 60G engines (two of which were funded primarily by the Commission) were designed to improve the commercial viability of the engine in heavy-duty trucking applications in the following ways: 1) improve the power, driveability and durability of the early-model S60G engine, to meet rigorous requirements of today's Class 8 trucks, 2) further reduce emissions and achieve certification of the engine to California's Optional Low-NOx Emission Credit Standards, and 3) improve fuel efficiency, if possible. In addressing these objectives, DDC included the following specific hardware and software modifications in its initial upgrade kit:

- **Advanced ignition system:** A new ignition system with state-of-the-art coil-on-plug technology was installed to ensure complete combustion, with no external secondary spark plug wires, and improve spark-plug life.
- **Advanced fuel metering:** A re-mapped fuel system was developed to refine fuel control. The regulator was re-configured to allow the use of a single unit in place of the original two regulators. The fuel control system was entirely engine mounted for more compact packaging and better fuel flow.
- **Improved combustion control:** A new closed-loop system incorporating an exhaust temperature sensor and an exhaust oxygen sensor was utilized. The exhaust O<sub>2</sub> sensor provides constant feedback to the Engine Control Module (ECM) to ensure proper air/fuel ratios. The control system also has adaptive learning capability to update and refine the engine performance and derivability.
- **Other selected engine hardware:** Selected internal engine components were installed to improve durability and reduce oil consumption.

##### 3.1.1 Engine Upgrade for Tractor #1 (Funded by DOE/NREL)

In late 1998, as part of the project funded by the SCAQMD and NREL, ADLittle established a subcontract with DDC to procure the necessary parts and perform an in-chassis upgrade to the 1<sup>st</sup> Series 60G engine. In parallel, a subcontract was executed with JBK to cover the incremental costs of purchasing the 1<sup>st</sup> existing LNG tractor with a first-generation (essentially obsolete)

S60G engine. The JBK subcontract was quickly completed, and in late 1998 the first tractor was delivered to VDDA in Industry, CA. In January 1999, DDC delivered to VDDA all the needed components for the upgrade package, including cylinder kits, a new turbocharger, a fuel metering system, a fuel pressure regulator, an electronic controller, and a coil-on-plug ignition system.

During January 1999, DDC and VDDA performed this first engine upgrade using the upgrade kit and parts supplied by DDC. In tandem, ADLittle inspected the chassis and on-board LNG fuel system to identify needed upgrades. ADLittle worked with VDDA to determine that the tractor's LNG fuel system was in proper working condition. ADLittle then coordinated with VDDA and JBK to ensure that various other repairs and upgrades were performed, to ensure that the tractor was ready for on-road use. The entire process of upgrading the DDC S60G engine and tractor chassis was completed in late January 1999. Table 3-1 lists the final specifications for the first LNG tractor after the engine upgrade. With minor modifications (to be described), the 2<sup>nd</sup> and 3<sup>rd</sup> LNG tractors were subsequently built to these same specifications, primarily under the Commission-funded project with a small cost share from SCAQMD.



**Figure 3-1. LNG Tractor #1 at VDDA during its engine upgrade**



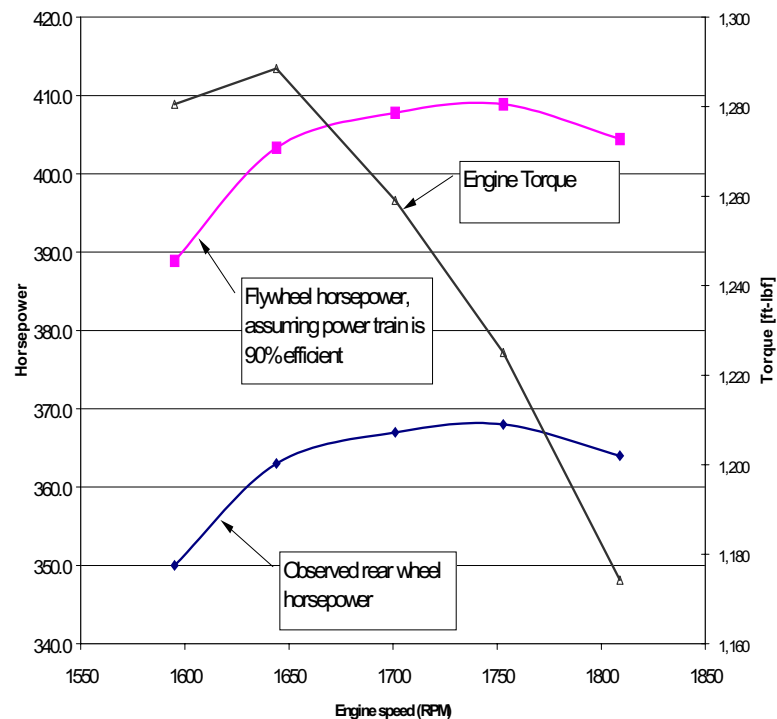
**Figure 3-2. DDC S60G engine during the upgrade to 400 hp / 1450 lbs-ft.**

**Table 3-1. System specifications for LNG tractors**

<b>ENGINE</b>	
Type	Detroit Diesel 400-hp Series 60G LNG
Compression Ratio	10:1
Rated Power	400 HP @ 2100 rpm
Peak Torque	1450 lbs-ft @ 1200 RPM
Displacement	12.7 Liters
Engine Control	DDEC IV, on-engine
Ignition	Electronically controlled, with coil on plug ignition
Engine Oil	40 quart capacity, special Mobil Delvac Super Geo oil for natural gas engines
<b>CHASSIS &amp; DRIVETRAIN</b>	
Chassis Type	1994 Freightliner FLD 120
GVWR	80,000 lbs.
Cab	Conventional
Transmission	Rockwell, model #RM-10-145A
<b>FUEL SYSTEM</b>	
LNG Tanks	2 MVE LNG tanks, model #HLNG 119, manufactured in 1995, net volume: 107 gallons; operating pressure: 120 psi Equipped with Parker nozzles Not equipped with vapor return fittings
Lines	Fill lines interconnect but a check valve prohibits filling both tanks from one side
LNG Vaporizer	Existing 1994-model MVE vaporizer for 300 HP HD engines was retained <sup>6</sup>
<b>EMISSION CONTROL SYSTEM</b>	
Engine system	Lean calibration using speed-density airflow measurement, electronic fuel metering valve, engine control module and exhaust gas oxygen sensor; turbocharger with wastegate, recirculation valve, and air-to-air charge cooling; optimized ignition timing.
Sensors	Knock sensor, engine coolant temperature and level sensors, and exhaust gas temperature sensors are used by DDEC controller for engine protection purposes
<b>DATA ACQUISITION EQUIPMENT &amp; SENSORS</b>	
Data Logger	Integral data logging features of DDEC IV ECM
Road Relay	DDC device that translates engine fault codes to English
Methane Detection System	AMEREX AMDGAS III methane detection system. First sensor located over engine fuel metering system. Second sensor located between the bulkheads of the twin LNG tanks (later relocated to the cab interior to be consistent with SAE J2343 and to prevent contamination by road debris).

<sup>6</sup> The original LNG vaporizers (heat exchangers) were deemed adequate for the upgraded, higher-horsepower S60G engines. However, it's possible that downstream driveability problems were related to vaporizer overloading.

Following its engine upgrade, checkout testing was performed on Tractor #1 in preparation for its delivery to JBK. To assess the upgraded system's horsepower and torque, DDC and VDDA tested the tractor on VDDA's chassis dynamometer. During this testing, the tractor developed 368 hp at the rear wheels, which is equivalent to slightly more than 400 bhp at the flywheel. This test confirmed that the tractor would be able to meet the performance standards requested by JBK. ADLittle analyzed the raw data provided by VDDA and produced the graph in Figure 3-3 below.



**Figure 3-3. Performance testing results for Tractor #1 on VDDA's chassis dynamometer**

### 3.1.2 Engine Upgrades for Tractors #2 and #3

Following execution of the grant agreement with the Commission in August 1999, Arthur D. Little executed new subcontracts with JBK and DDC to: 1) pay for the incremental cost of two additional existing LNG tractors, 2) perform engine upgrades to their older S60G engines, and 3) add these newly upgraded LNG tractors to the JBK demonstration (described in next section). Engine upgrades for Tractors #2 and #3 were performed under Commission funding with a cost share of \$13,379 from the SCAQMD. This process increased the number of LNG tractors in the Class 8 truck demonstration from one to three. (Refer back to Table 2-1 on page 2-4 for a description of this arrangement, and how each of the three LNG tractors was funded.)

The engine upgrades for Tractors #2 and #3 were completed on October 1, 1999 (see photographs). Both vehicles underwent checkout testing by VDDA on a chassis dynamometer before final delivery to the JBK depot in Fontana. Similar performance results to LNG Tractor #1 were obtained.



**Figure 3-4. LNG Tractor #2 is towed to the Ontario L/CNG station for initial fueling after its engine upgrade.**



**Figure 3-5. LNG Tractor #3 undergoes performance testing on the VDDA dynamometer.**

### **3.2 TASK 1 — Field Demonstration**

#### **3.2.1 12-Month Demo of LNG Tractor #1 (SCAQMD and NREL Funding)**

The one-year demonstration of LNG Tractor #1 under SCAQMD and NREL funding began in early February 1999, when the tractor was towed to the Ontario LNG fueling station for its first LNG fueling. As a prelude to deployment in revenue service, JBK staff and ADLittle's field

engineer performed on-road checkout testing. During the test drive, the engine ran well and accelerated strongly, with almost none of the hesitation or misfiring that frequently occurred in earlier versions (pre-upgrade) of the S60G engine. However, blue smoke and the odor of burning lubricating oil were also detected. This was thought to be due to poor performance of the oil-control rings prior to ring break-in and seating. ADLittle and JBK monitored oil consumption during the field demonstration and worked with DDC to resolve the observed problem (see 3.2.7.4 Oil Analysis and Consumption).

Following this inaugural on-road test run, a preliminary load test was run. However, when JBK's trailer was hooked up to the tractor, the power take-off (PTO) shaft and alternator on the truck were slightly damaged. JBK mechanics were able to resolve this problem, and the load test was conducted. Both DDC and JBK staff concluded that the LNG tractor provided sufficient horsepower and torque to perform in the intended service, i.e., Class 8 trucking at the full 80,000 lbs. GVWR.

LNG Tractor #1 began service as part of JBK's southern California fleet on February 9, 1999. A JBK tractor with the DDC Series 60 diesel engine (#961853) was designated as the diesel control tractor. However, in June 1999 JBK decided to relocate this particular truck to Alabama. ADLittle worked with JBK staff to designate a new diesel S60 tractor (#961857) as the control vehicle. Data collection for the second diesel control tractor began on July 13, 1999.

The LNG tractor ran extremely well throughout the initial nine months of demonstration, and was well received by its drivers. No emergency road calls were needed and the vehicle averaged approximately 5,000 miles per month. The only significant problem encountered was excessive oil consumption. At the quarterly project review meeting with SCAQMD, NREL and the Commission in mid 1999, DDC indicated that the probable cause of the high oil consumption was rings that had been improperly installed in one or more of the six cylinders. At this time, with DDC's recommendation, the various project participants agreed to continue accumulating mileage on the tractor.

In late 1999, after accumulating more than 47,000 miles of service, Tractor #1 was removed from service to troubleshoot the oil consumption issue and perform various engine and chassis upgrades. Ultimately, additional time was needed by DDC to perform calibration upgrades to the engine in parallel with its emissions certification efforts (see Task 2). Thus, Tractor #1 was used in intermittent service for the next two months. Still, when the SCAQMD/NREL-funded demonstration ended in early February of 2000, the truck had accumulated about 48,000 miles and was operational approximately 80% of the time, excluding the time needed to perform calibration upgrades.

### **3.2.2 Commission Subtask 1.1 – Delivery and Integration of 2<sup>nd</sup> and 3<sup>rd</sup> LNG Tractors**

In October 1999, Tractors No. 2 and No. 3 were delivered to JBK for the start of their demonstration. However, a combination of factors resulted in limited mileage accumulation for both tractors. Both tractors entered service at JBK by November 2, but exhibited engine problems such as low power, surging, and misfiring. In particular, the trucks ran well immediately after fueling, but engine performance would deteriorate a few hours into operation. Pressure gauges installed just upstream from the engine inlet pressure regulators showed that this

behavior was associated with the fuel pressure falling from approximately 150 psi to 60-70 psi. DDC worked with its affiliate, VDDA to resolve this problem by making various adjustments to the on-board LNG fuel systems, as further described in 3.2.7.7.

### **3.2.3 Subtask 1.2 – Coordination of DDC Subcontract and Field Support**

Technical as well as human-related problems tend to occur with greater frequency during demonstrations of prototype or commercially immature vehicle technologies. Under the structure of the two related project and contracts, ADLittle was in charge of ensuring that comprehensive field support was provided for all three LNG tractors during the demonstration. Assisting ADLittle under subcontract for this work were DDC and VDDA. Throughout the two projects, ADLittle, DDC and VDDA worked to address and resolve any problems as quickly as possible. JBK also expended significant resources to resolve problems that typically occur during demonstrations of prototype or commercially immature technology.

As previously noted, Tractor #1 operated with few major problems for most of the first nine months, under SCAQMD and NREL funding. The two events that required the most coordination were the actual engine upgrade and the repairs for high oil consumption. Additional problems occurred during the deployments of LNG tractors #2 and #3. Details about the problems encountered during the demonstration, and how they were resolved, are provided in Section 3.2.7.

Part of ADLittle's efforts to provide comprehensive field support involved the need to obtain any necessary permits and certifications to operate the three LNG tractors on public roads. Activities that ADLittle coordinated in this regard included the following:

- Contacted the California Highway Patrol (CHP) to assess the latest LNG-related requirements under Title 13 of the California Code of Regulations,<sup>7</sup> and obtained a letter from the CHP and delivered it to JBK
- Applied for and received experimental vehicle permits from ARB for all three LNG trucks, enabling them to be operated as emissions prototypes in California
- Inspected each tractor for compliance with California Title 13, and contacted the fuel system manufacturer, Minnesota Valley Engineering (MVE), about the specifications to which the fuel system was designed
- Purchased and installed Parker LNG fill receptacle covers and MVE excess flow check valves
- Fabricated and installed labels for various components of the on-board LNG fuel systems, as required by Title 13 and/or SAE J2343 (see Table 3-3)
- Provided fuel system troubleshooting, repair and upgrades

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<sup>7</sup> *Title 13: Motor Vehicles* under the California Code of Regulations includes sections that address on-board fuel systems, with special requirements for LNG trucks (see Table 3-3).

### 3.2.4 Subtask 1.3 Site Visits and Troubleshooting

A key part of ADLittle's technical support for the two projects involved making periodic site visits to JBK's Fontana depot, to ensure that the vehicles were working properly and being used as much as possible by JBK. In addition, periodic visits were needed to VDDA in the City of Industry, to document work performed on the LNG tractors beyond scheduled maintenance. Table 3-2 provides a summary of the site visits conducted by ADLittle staff, and the work performed. Figure 3-6 and Figure 3-7 show photos of the types of activities ADLittle coordinated during those site visits.

**Table 3-2. Summary of Site Visits and Work Performed by ADLittle Staff**

Date	Location	Work Performed
November 1999	VDDA, Industry, CA	Observed and assisted VDDA and Northstar in performing fuel system upgrades on LNG #2 and #3. Upgrade included repairs to the left LNG tank on LNG #3, and restoration of its vacuum to Chart-MVE's specifications.
December 1999	JBK Depot, Fontana, CA	Visited JBK to investigate reports that LNG #3 was exhibiting low fuel pressure and reduced power. Provided new excess flow check valve following extensive troubleshooting of the fuel system.
September 29, 2000	JBK Depot, Fontana, CA	Met with JBK personnel, inspected trucks, recorded odometer readings.
October 12, 2000	VDDA, Industry, CA	Met with VDDA and DDC personnel. Inspected LNG #2, and recorded the odometer reading. DDC engineer identified several mechanical problems with the truck.
November 3, 2000	VDDA, Industry, CA	Met with DDC engineer, inspected JBK LNG trucks for repairs.
February 1, 2001	JBK Depot, Fontana, CA	Met with JBK site foreman and VDDA technician. Inspected LNG #2, which had received fuel system upgrades and refurbished MVE LNG tanks. Discussed post-upgrade operational problems and possible solutions.
February 22, 2001	JBK Depot, Fontana, CA	Met with personnel from VDDA, MVE-Chart, Applied LNG Technologies, and JBK to troubleshoot problems with LNG #1 and #2 – the two JBK trucks currently on-site.
April 9-10, 2001	JBK Depot, Fontana, CA	Attended, documented and photographed training session led by VDDA personnel on April 9-10, 2001 (cost-shared with funds from the Mobile Source Air Pollution Reduction Review Committee).
June 14, 2001	JBK Depot, Fontana, CA	Met with JBK's site manager to collect operating and maintenance data for the LNG trucks and diesel control, and discuss the project's upcoming conclusion.
September 25, 2001	Vons Truck Depot, Santa Fe Springs, CA	Conducted interview with Vons shop foreman to assess experience with S60G-equipped LNG tractors.



**Figure 3-6. Restoration of vacuum on Tractor #3's left LNG tank, November 1999**



**Figure 3-7. Documentation of LNG tractor daily rollout at JBK, December 1999**

### 3.2.5 Subtask 1.4 – Design Improvements and Upgrades During Project

#### 3.2.5.1 Certification Upgrades to Series 60G Engines

Working with ADLittle and VDDA, DDC performed several design improvements on the three S60G engines during the course of the project. This process began with LNG Tractor #1 just before the Commission-funded demonstration began, and continued throughout the project. The main driver for these upgrades was the emissions certification testing that DDC conducted in December 1999, which produced additional engine data for calibration refinements (also see Task 2 in Section 3.3).

The most significant upgrade involved the engine control module (ECM) program used in the certified 400-hp Series 60G, known to DDC as “Release 27.” One feature of the Release 27 program is that it provides for fuel shut-off while the engine is being motored, which eliminates or reduces exhaust emissions during motoring.<sup>8</sup> DDC installed the Release 27 ECM program in Tractor #1 when it became available in early 2000, and subsequently in Tractors #2 and #3. Calibration changes were also made to lookup tables controlling air/fuel ratio and spark advance.

Initially, when DDC installed Release 27 in LNG Tractor #1, the program required further development. DDC restored the earlier, uncertified ECM program (known as “Release 24”) along with the previous calibration, while diagnosing the cause of the problem with Release 27. The problem was traced to a conflict between ECM instructions for maintaining the correct high idle speed when a power takeoff (PTO) accessory is used, and the new instructions for shutting off fuel flow during motoring. Since the LNG tractors were not equipped with PTO shafts,<sup>9</sup> DDC resolved the problem by disabling the instruction set for PTO operation. In mid 2000, DDC and VDDA reinstalled the Release 27 program along with a new calibration in Tractors #1, #2, and #3.

This configuration revealed a new problem. The new calibration exhibited lean misfire and poor throttle response when used with the existing low-pressure fuel regulator made by Impco. This Impco low-pressure regulator exhibited variability in flow behavior among individual units, due to manufacturing tolerances. According to DDC, the problem typically had to be resolved by replacing the Impco regulator once, or sometimes twice, before a satisfactory unit was installed.

DDC further investigated the link between the new calibration and problems with the Impco low-pressure regulator. Compared to the previous ECM calibrations, air/fuel ratios at both low and full load required more fuel under the new calibration than the regulator could supply. The previous calibration’s excess air ratio ( $\lambda$ ) was approximately 1.5 (equivalent to 25.8:1 mass air/fuel ratio). Release 27 increases  $\lambda$  at these loads by approximately 0.03<sup>10</sup>. It also incorporates somewhat richer air/fuel ratios at high part-load cruise and during acceleration. This control strategy apparently makes the engine more sensitive to manufacturing variability in regulator

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<sup>8</sup> While motoring, the engine is being driven by the drivetrain. In this mode, it functions as a compressor that absorbs power from the flywheel.

<sup>9</sup> None of the LNG tractors were initially deployed with PTO shafts. As part of its conversion to a Mobile Refueling Truck (MRT), LNG #1 was later equipped with a PTO system, which allows the MRT to provide 110 VAC power to the refueling station.

<sup>10</sup> Roger Parry, Program Manager, Alternative Fuels Group, Detroit Diesel Corporation, personal communication with Jon Leonard and Richard Remillard, 7 June 2000.

performance. As of the writing of this report, DDC and IMPCO were working to resolve this problem.

### 3.2.5.2 Safety and Title 13 Upgrades

On several occasions after all three LNG trucks were on the road, ADLittle communicated with Chart-MVE (the fuel system manufacturer) to assess if any system upgrades were needed. During the early months of the demonstrations, no changes were required. However, it eventually became necessary for ADLittle to implement several safety and labeling changes, to conform with evolving requirements from the California Highway Patrol (CHP) and comply with *Title 13: Motor Vehicles* of the California Code of Regulations. Table 3-3 lists the LNG truck and tank issues that were addressed by ADLittle, to comply with Title 13.

**Table 3-3. LNG Truck and Tank Adjustments to Obtain Title 13 Compliance**

<b>Title 13 Requirement</b>	<b>Potential Violation Condition</b>	<b>Action taken by ADLittle</b>
Tank must be labeled with "CHP" and the service pressure	No such label exists.	Created and applied proper label.
Fill receptacle shall be labeled with "FOR LNG ONLY" with letters not less than 1 in. high.	No such label exists.	Created and applied proper label.
All inlets and outlets except relief valves and gauging devices shall be marked to designate if they communicate with vapor or liquid space.	Valves are labeled as "fill", "liquid" and "vent". These labels are likely too ambiguous to meet this provision.	Created and applied proper label.
Discharge (cracking) pressure of safety relief valves (PRVs) shall not exceed 125% of the service pressure of the container.	Primary PRV cracking pressure is 250 psi. Therefore, this language requires that the service pressure be no less than 250 psi /1.25, or 200 psi. The tank service pressure should be labeled as being 200 psi, to meet this provision.	Created and applied proper label.
One manually operated shut-off valve shall be secured directly to the tank vapor outlet with no intervening fitting other than the relief valve and shall be marked with the words "VAPOR SHUT-OFF VALVE".	Valve is labeled as "VENT".	Created and applied proper label.
Another manually operated shut-off valve shall be secured directly to the tank liquid outlet and shall be marked with the words "LIQUID SHUT-OFF VALVE".	Valve is labeled as "LIQUID".	Created and applied proper label.
[LNG fuel] Containers located less than 8 in. from the engine or exhaust system shall be shielded against direct heat.	The right fuel tank is located within 2 inches of the exhaust line, close to where the line enters the cab-mounted muffler. There is no shielding between the exhaust line and the tank.	Coordinated with VDDA for installation of heat shield.
All remote filling inlets shall be visibly marked with the lowest working pressure of any fuel supply container in the system.	No such label exists.	Created and applied proper label.
[Pressure relief] lines shall ... direct escaping gas upward within 45 deg of the vertical.	The pressure relief line discharges near the top of the cab, through a nozzle that directs the discharge horizontally toward the rear of the truck.	Requested JBK to modify pressure relief lines per requirement
[Pressure relief line] outlets shall be protected by caps, covers, or other means to keep water or dirt from collecting in the lines. Protective devices shall not restrict the flow of gas.	The horizontal discharge line opening is uncapped, but is mitered at 45 degrees, with the longest end at the top, which tends to prevent the entry of rain.	Requested JBK to modify pressure relief lines per requirement
A normally closed automatic shut-off valve [downstream of the fuel tank outlet manifold] held open by electrical current may be used in lieu of a manual shut-off valve and shall be marked with the words "AUTOMATIC SHUT-OFF VALVE".	An automatic shut-off valve exists, but is not labeled. The upgraded engine will use a different shut-off valve that should be labeled.	Created and applied proper label.
[Fuel] Supply lines shall be supported at least every 24 in. and shall be prevented from sagging.	Trucks have at least one length of 1" diameter (OD) stainless tube fuel line that runs about 28" between supports.	Added new supports for supply lines.

### 3.2.6 Subtask 1.5 – Methane Detectors

The original purpose of this subtask was to regularly inspect each LNG tractor's on-board methane detector to ensure proper operation at all times. However, after the three used LNG tractors were actually delivered to California from Praxair in Texas, ADLittle learned that none of the tractors were equipped with methane detection systems (at the time, Texas did not require methane detection on LNG trucks). As was the case for LNG Tractor #1 funded by SCAQMD and DOE/NREL, ADLittle purchased two state-of-the-art AMEREX methane detection systems to bring Tractors #2 and #3 into compliance. Among other features, this system is self-calibrating and does not require a special inspection program. In November 1999, VDDA installed this methane-detection system in Tractors #2 and #3. The photo below shows the AMEREX methane detection system's display inside the cab of Tractor #1 (installations for Tractors #2 and #3 were essentially identical). Original locations selected for the actual methane detectors were over the engine's fuel metering system and under the frame between the twin LNG tanks; adjustments were subsequently made, as described below.



**Figure 3-8. In-dash AMEREX methane detector display in cab of each LNG tractor**

The JBK driver of LNG Tractor #1 reported false-positive readings on the AMEREX system in August 1999 (before the Commission-funded demonstration began). After the fuel system was inspected and verified to be leak-free, ADLittle contacted the AMEREX dealer to discuss diagnostic and cleaning procedures for the methane detection system. It was concluded that the location of one detector had possibly contributed to the false positives due to contamination by road debris. No further false-positive readings occurred for several months. In November 1999, ADLittle determined that one of the detectors should be relocated to the cab of the truck, to comply with California Title 13 and SAE standard J2343. This would also reduce false-positive readings from road debris. JBK was informed of the need to move the detector location, and performed the work as a cost share to the project. No subsequent false-positive readings were reported on Tractor #1.

Methane detectors for Tractors #2 and #3 were installed in a similar fashion, when the engine upgrades were performed in late 1999. No false-positive readings were reported on these two LNG tractors during the demonstration.

### 3.2.7 Subtask 1.6 – Operating Data

ADLittle asked JBK staff at the Fontana depot to collect the following data parameters during the course of the demonstration for the LNG and diesel control tractors:

- Fuel consumption (with mileage and date)
- Oil consumption (with mileage and date)
- Routine maintenance (with mileage and date)
- Road calls (with mileage and date)
- Driver evaluations (as needed)

To facilitate the recording and transfer of these data on a regular schedule, ADLittle prepared data collection forms and set up data logbooks for each LNG tractor and the diesel-control tractor. ADLittle worked with JBK staff to collect the required data, and fax it monthly for compiling, analyzing and reporting in progress reports to the Commission, SCAQMD and NREL.

Regular data collection began in February 1999, when Tractor #1 entered revenue service under NREL/AQMD funding. Data collection for LNG tractors #2 and #3 began on November 2, 1999, and data collection for tractor #1 and the diesel control phased from NREL/AQMD funding to Commission funding on February 9, 2000. As further described in the following sections, effective collection of detailed operating data was significantly hindered by employee turnover at JBK's Fontana depot.

#### 3.2.7.1 Cumulative Months Available for Operation

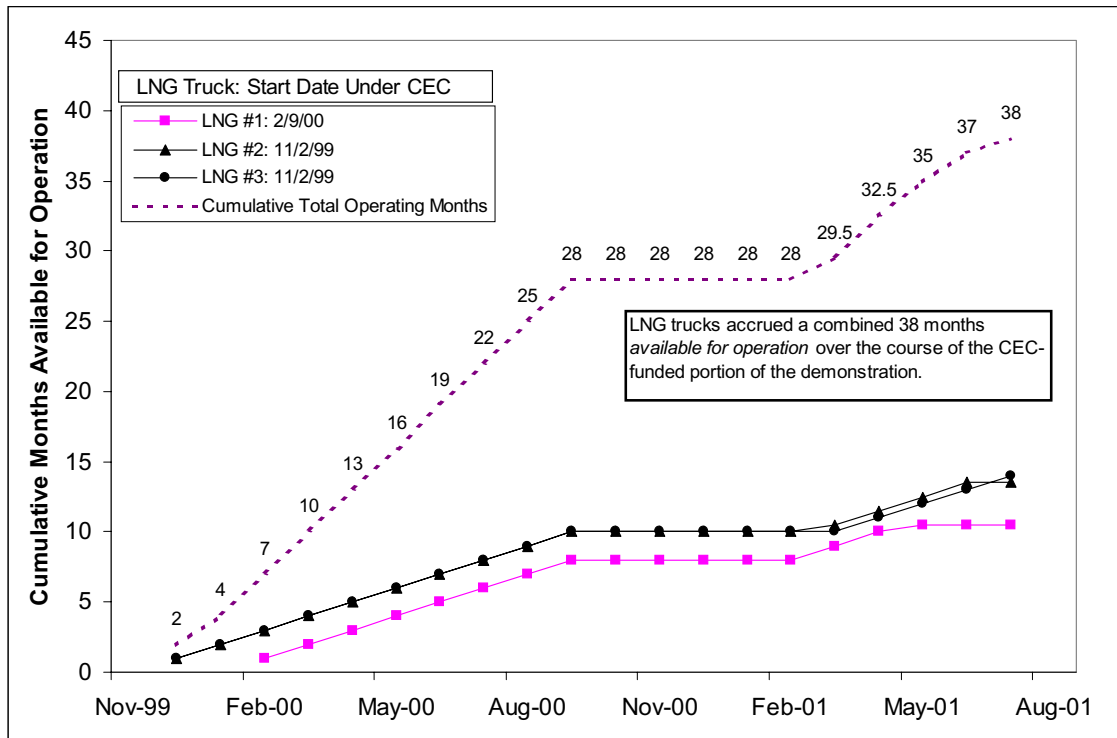
One objective of the demonstration was to accumulate as many miles on the LNG tractors as possible, while displacing significant volumes of diesel fuel. The three LNG tractors were targeted to be *available* for up to 42 months<sup>11</sup> of collective operation, to be driven whenever suitable for JBK's normal revenue service. In addition, the projects were designed to always have at least one LNG tractor available for display at conferences and events, to highlight the anticipated commercial availability of a high-horsepower, high-torque LNG engine for Class 8 trucking applications.

ADLittle monitored the operational status for each of the three prototype tractors over the course of the two related demonstrations. The lone LNG tractor (#1) in the SCAQMD and DOE/NREL demonstration performed very well and accumulated more than 45,000 miles in its first nine months of deployment. Under the Commission-funded demonstration, the three LNG tractors (#1, #2, and #3) performed well at times and were mostly available for operation. However, the trucks were not operated for significant periods of time, generally due to one of the following reasons: 1) upgrades to engine and/or fuel systems were being performed, 2) there was a lack of LNG-trained drivers due to employee turnover at JBK's Fontana depot, and 3) engine and/or fuel system problems were experienced. These factors are discussed in greater detail below. Figure

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<sup>11</sup> This was based on the goal of achieving 18 months each for Tractors #2 and #3, and extending the demonstration for Tractor #1 by 6 months ( $18 + 18 + 6 = 42$ ). Achieving at least 66% the 42 collective months (in any combination) was a contract requirement, barring catastrophic failure of any vehicles.

3-9 provides a timeline of how successful demonstration months were accrued, individually and collectively.



**Figure 3-9. Months Available for Operation under Commission Funding (LNG Tractors)**

### 3.2.7.2 Mileage Accumulation and Driving Route

LNG tractors #1, #2, and #3 accumulated 69,901, 33,325, and 13,214 miles, respectively during the demonstration. By contrast, the diesel control tractor<sup>12</sup> accumulated much more mileage (140,396 miles) over roughly the same period. Table 3-4 provides a comparison of the demonstration mileage for the LNG tractors and the diesel control tractor. Figure 3-10 depicts more detailed information as a function of the demonstration timeline.

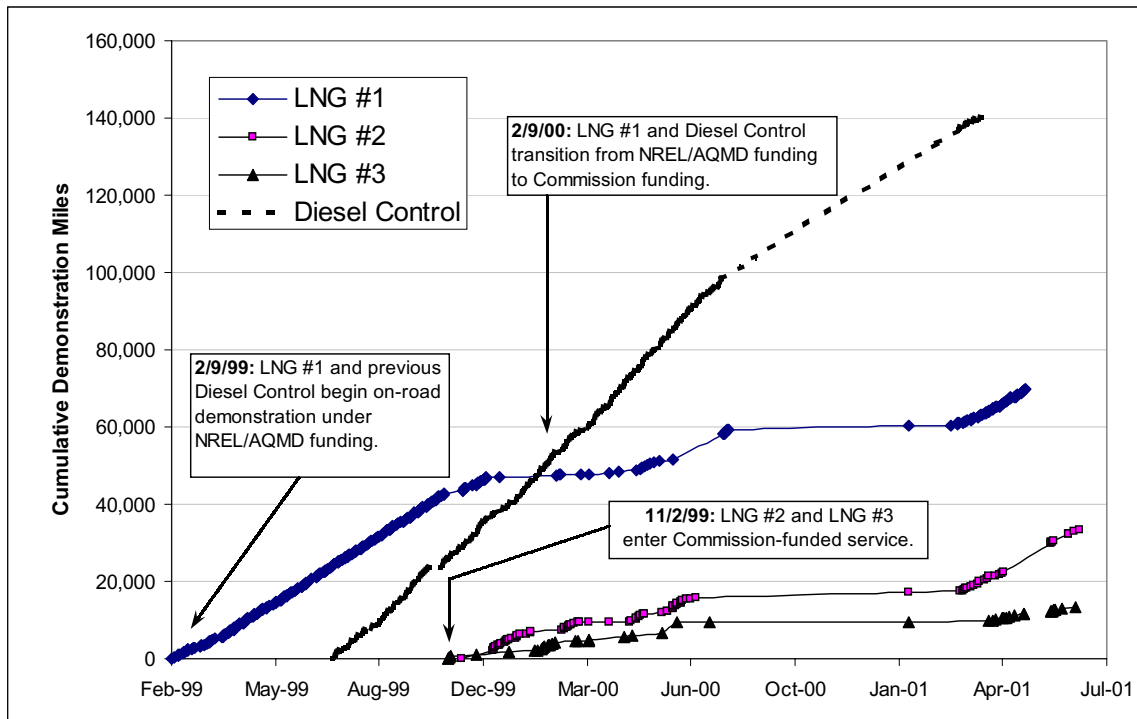
In part, the reduced mileage for the LNG tractors compared to the diesel control can be attributed to the downtime factors described in the previous section. However, there was another key factor that highlights a significant barrier for expanded use of LNG engines in long-haul trucking applications. JBK's diesel control tractor provided sufficient range to make long-haul deliveries into neighboring western states and Mexico – this is the combined result of three main factors: 1) high energy density of diesel fuel, 2) inherently high efficiency of compression-ignition engines, and 3) widescale availability of diesel fuel. By contrast, range limitations of the LNG tractors (see Section 3.2.7.3) and the paucity of LNG fueling stations outside Southern California made it

<sup>12</sup> As noted previously, “diesel control tractor” refers to the collective, in-series mileage accumulation of two different tractors powered by DDC Series 60 diesel engines.

impossible for JBK to use the LNG tractors on similar routes, confining their use to shorter-distance local hauls. As a result, the LNG tractors were driven an average of about 300 miles per day, as compared to the diesel control, which was driven approximately 500 miles per day.

**Table 3-4. Summary of miles accumulated by LNG tractors compared to diesel control**

Truck	Demonstration Mileage	% of Diesel Control
LNG #1	69,901 <sup>13</sup>	50%
LNG #2	33,325	24%
LNG #3	13,214	9%
Diesel Control	140,396	--



**Figure 3-10. Cumulative Demonstration Miles for the LNG and Diesel Control Tractors**

<sup>13</sup> 69,901 reflects the total mileage accrued by LNG Truck #1 under both the AQMD/NREL demonstration (47,168 miles) and the follow-on effort funded by the Commission (22,733 miles).

The above tables and figures reflect information from the full LNG truck program (i.e., including the first 12 months of operation for LNG Tractor #1 under SCAQMD and DOE/NREL funding). Table 3-5 provides a comparison of the daily miles and time in service for the LNG tractors and diesel control tractor during the Commission-funded demonstration only.

**Table 3-5. Comparison of Daily Mileage and Time in Service for LNG and Diesel Tractors**  
(Commission-funded portion of demonstration)

Parameter	LNG Truck #1 <sup>14</sup>	LNG Truck #2	LNG Truck #3	Diesel Control <sup>15</sup>
Days In Operation	71	83	46	179
Average Daily Mileage	319	281	287	493
% of Days in Service Compared to Diesel	40%	46%	26%	100%

To assess performance and document the “typical” driving route for the LNG tractors, ADLittle conducted a ride-along with Tractor #1’s driver on March 23, 1999. From that trip and further discussions, it was determined that an average local delivery in the Los Angeles area consisted of about 50,000 lbs. of liquefied nitrogen (LN<sub>2</sub>). Such a trip typically took approximately two hours and included a combination of freeway driving, surface-street driving, and extensive engine idling. Three to four round-trip deliveries were made each day, consisting of about 80 to 90 miles. Fully loaded, the tractor and trailer weighed 80,000 lb. This duty cycle served as a good test for the types of heavy-duty vehicle applications that are targeted commercial applications for the DDC Series 60G LNG engine, such as grocery store operations.

On the day of the drive-along test, LNG Truck #1 was driven up an estimated 5% grade with a peak elevation of 3,500 feet.<sup>16</sup> Carrying a combined load that day of approximately 60,000 lbs., the tractor was able to climb the grade at 45 mph and provide diesel-equivalent power, according to the driver.

### 3.2.7.3 Fuel Economy and Vehicle Range

Over the course of the demonstration, operating data were collected by JBK and provided to ADLittle for analysis. Typically, JBK drivers recorded daily mileage and fueling amounts. Fuel economy calculations were derived on a miles-per-volume-of-fuel basis, by summarizing and utilizing these data. The LNG tractors exhibited an average fuel economy of 2.48 miles per LNG gallon. The average fuel economy for the diesel control tractor was 5.80 miles per diesel gallon. Along with fuel tank capacity and duty cycle, these unadjusted (for energy equivalency) fuel

<sup>14</sup> In total, including both portions of the demonstration, LNG Truck #1 was operated 259 days and averaged 270 miles per day.

<sup>15</sup> In total, including both portions of the demonstration, the diesel control tractor was operated 352 days and averaged 296 miles per day.

<sup>16</sup> The climb consisted of State Route 14, from the I-5 exit to the high desert. Ambient temperatures were approximately 17 degrees Celsius at the bottom of the climb and 23 degrees Celsius at the highest elevation.

economy numbers are key determinants for the effective driving ranges of the tractors. Table 3-6 provides a comparison of the effective ranges for the LNG and diesel trucks, taking into account gross fuel capacity, net fuel capacity, and average fuel economy. The LNG tractors exhibited relatively poor fuel economy largely because spark-ignited natural gas engines are significantly less efficient than their compression-ignition (diesel) counterparts. In addition, the LNG tractors were primarily used in short-haul routes involving less-fuel-efficient duty cycles, and in general were used with greater day-to-day variation in duty cycle.

**Table 3-6. Range of LNG Tractors vs. Diesel Control Tractor in Demonstration Line-Haul Use**

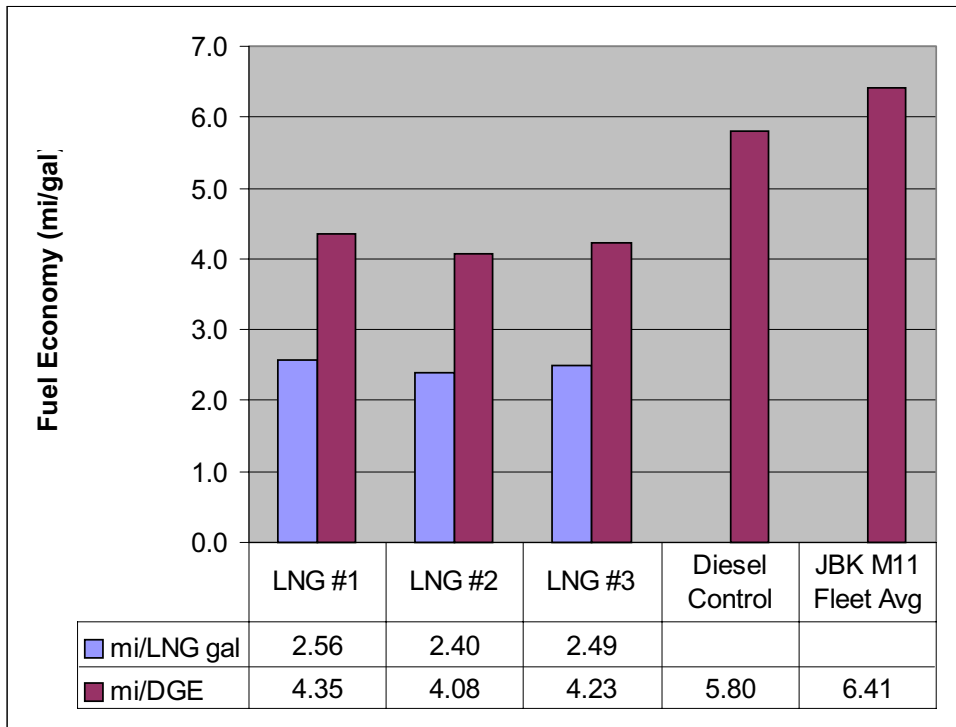
	<b>LNG Tractors</b>	<b>Diesel Control Tractor</b>
<b>Gross Fuel Tank Capacity</b>	240 gallons	200 gallons
<b>Net Fuel Capacity</b>	216 gallons <sup>a</sup>	200 gallons <sup>b</sup>
<b>Average Fuel Economy</b>	2.48 mpg(LNG)	5.80 mpg
<b>Effective Range</b>	535 miles <sup>c</sup>	1,160 miles
<sup>a</sup> Chart-MVE spec sheet for HLNG-119 model tank lists 90% capacity, primarily to provide ullage space, which prevents tank overfilling by accommodating expanding liquid. <sup>b</sup> Even diesel vehicles cannot be practically driven until every potential mile of range is utilized. However, the wide availability of fuel on the open road and the relatively high degree of accuracy for diesel fuel gauges enables drivers to effectively approach 100% utilization when needed – providing a high degree of driver confidence in vehicle range. <sup>c</sup> By contrast, LNG fuel gauges are less accurate, further reducing driver confidence in vehicle range. Thus, this range figure may be a best case.		

To compare the fuel economies of LNG- and diesel-fueled trucks on an equivalent energy basis, the average fuel economy of the LNG trucks was multiplied by a factor of 1.7016.<sup>17</sup> Applying this conversion yields an average fuel economy for the LNG trucks of 4.22 miles per diesel gallon equivalent (DGE). Volumetric (miles per gallon) comparisons calculated for the demonstration are presented in Figure 3-11, including a comparison of JBK’s average fuel economy for its fleet of trucks powered by Cummins M11 engines.

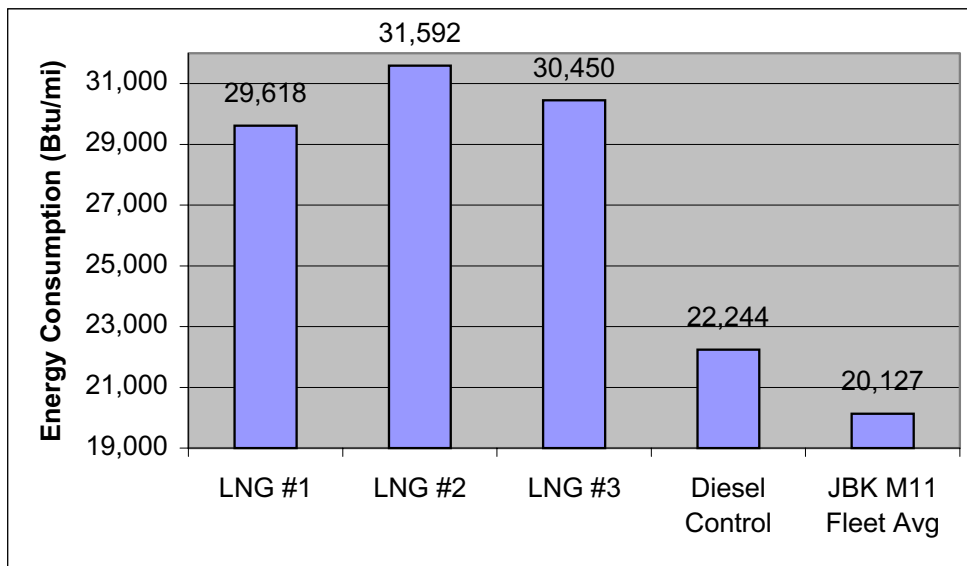
Figure 3-12 compares the average energy consumption (Btu per mile) of the LNG tractors, the diesel control vehicle, and the JBK M11 fleet average. In this graph, which is essentially the inverse of Figure 3-11, the lower energy consumption per mile of the diesel control and M11 fleet imply that these vehicles operate more efficiently. On average, the LNG trucks exhibited about 27% lower efficiency than the diesel control tractor, and 34% lower efficiency than JBK’s M11 fleet average.<sup>18</sup>

<sup>17</sup> This is the ratio of Btus (Lower Heating Value) in a gallon of diesel to a gallon of LNG, or 129,015 to 75,821, based on values that were derived as composites from numerous sources.

<sup>18</sup> It’s unknown if the Cummins M11 diesel engines powering most of JBK’s fleet were equipped with “defeat devices” that increase fuel economy at the expense of higher NOx emissions during on-road driving. In late 1998, the federal government settled a landmark legal case that accused seven major heavy-duty engine manufacturers (including Cummins) of illegally selling engines equipped with such devices.



**Figure 3-11. Average Monthly Fuel Economy Comparison**



**Figure 3-12. Energy Consumption Comparison in Btu / Mile**

Diesel engines operate under excess-air conditions and are inherently more efficient than spark-ignited engines, producing more power per energy consumed. However, there are other factors that likely contributed to the relatively low *calculated* fuel economy for the LNG tractors during the demonstration. These include the following:

- Excess LNG venting during refueling probably occurred periodically throughout the demonstration. Causes for this may have included 1) a lack of complete familiarity with LNG fueling procedures by JBK's drivers) and 2) non-optimized performance of various pressure relief valves and other on-board LNG fuel system components, some of which were replaced towards the end of the demonstration.
- Inaccuracy of fuel fills at the Ontario station, which did not receive the technology upgrade (including a more accurate dispensing system) under GRI and SCAQMD funding until the demonstration was complete (see 3.4.2).

### 3.2.7.4 Oil Analysis and Consumption

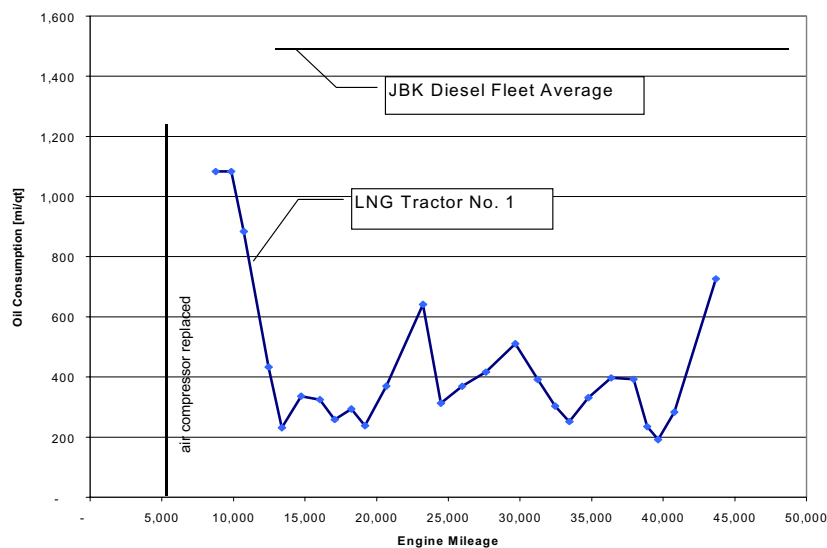
Under Subtask 1.4, ADLittle worked with JBK to track the use of engine oil for the LNG trucks and obtain oil sample reports, although high turnover at the Fontana depot significantly hindered the accuracy and regularity of the data collected. JBK's service schedule for diesel and LNG tractors calls for changing the lubricating oil at intervals of 15,000 miles, or 2 to 3 months. Oil samples were taken during oil changes; samples were then sent to Castrol labs for analysis. JBK forwarded the reports to ADLittle when and if any unusual results were found. Oil analyses for Tractors #1 and #2 indicated no problems during the demonstration. However, an oil analysis on Tractor #3 in December 1999 revealed likely lube oil contamination by engine coolant. Based on this analysis (Figure 3-13) VDDA diagnosed and repaired a failed oil seal in the water pump.

Oil Analysis Report Laboratory: Pennzoil JBK Fleet No.: 952270 Sample Date 12/15/99																			
Spectrochemical Analysis [parts per million]																			
Element	Iron	Chromium	Lead	Copper	Tin	Aluminum	Nickel	Silver	Silicon	Boron	Sodium	Magnesium	Calcium	Barium	Phosphorus	Zinc	Molybdenum	Titanium	Vanadium
Concentration	41	4	19	4	0	4	0	0	9	134	139	0	3104	0	1001	1690	2	0	0
Abnormal											A								
Critical																			C
Physical Properties																			
	Viscosity [cSt @ 100C]	Water [%]	Soot / Solids	Glycol															
Result	14.52	<.1	0.9	POS															
Abnormal																			
Critical				C															
Analysis recommendations:																			
Severe level of coolant (glycol) detected. Inspect for source of internal leak. Change oil and filter if not done at time of sampling. Resample at one-half normal interval. Results reported by phone / fax.																			

**Figure 3-13. Oil Analysis on LNG Tractor #3, December 1999**

Oil consumption was monitored between oil changes, by recording the date and odometer reading at which make-up oil was added, and the volume of oil added. Early in the demonstration, records indicated that oil consumption for Tractor #1 was high. Initially, it was assumed that the high consumption rate was related to engine break-in behavior, but after the problem continued for approximately 5,000 operating miles, this was eliminated as the cause. Inspection of the engine indicated that the air compressor was part of the high oil consumption problem. Since it shares a common lubricating oil supply with the engine, high lube-oil consumption rates can result when the air compressor has worn or damaged rings. However, after DDC and VDDA replaced the compressor with a remanufactured unit, only a marginal improvement was observed in oil consumption.

Oil consumption remained high for LNG Tractor #1 over its first nine months of demonstration. As Figure 3-14 shows, the oil consumption rate showed high month-to-month variability, and on average one quart of makeup oil had to be added for every 400 miles driven. Over the same time period, JBK reported that its diesel fleet averaged about 1,500 miles per quart of makeup oil.<sup>19</sup> As a near-term solution to offset JBK's high cost of oil for the tractor, DDC purchased a barrel of oil for the tractor. Per agreement of DDC and all project participants, Tractor #1 continued to accumulate mileage in the JBK fleet until November 1999, when the second and third LNG tractors could be deployed, under the related Commission-funded project.



**Figure 3-14. Oil Consumption Rates, LNG Tractor No. 1 (Before Ring Repair)**

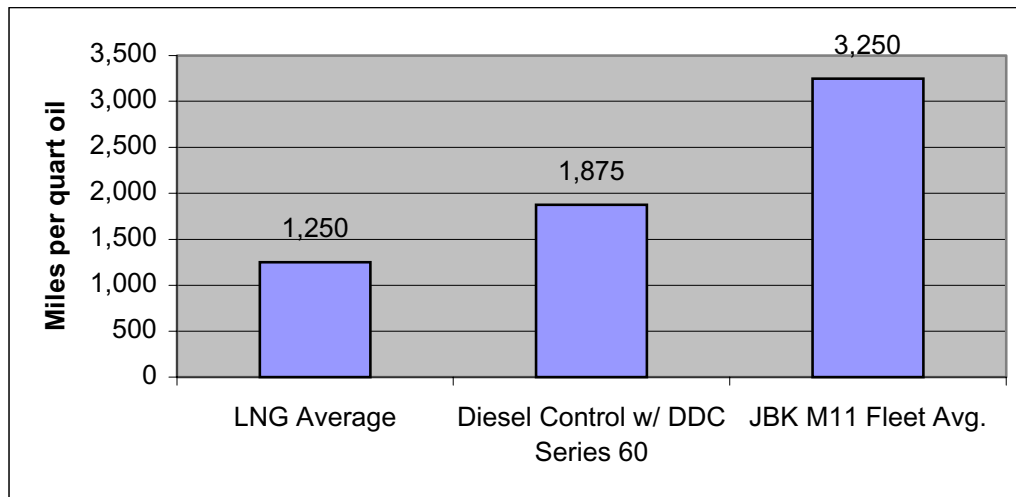
During further diagnostics of Tractor #1's engine at VDDA in November 1999, cylinder No. 6 showed fairly heavy oil fouling on the spark plug. VDDA and DDC personnel agreed that the ring pack in this cylinder was probably either improperly installed, or defective. Servicing for the ring problem occurred in December 1999, and extended through the completion of the

<sup>19</sup> It must again be stressed that JBK's Fontana fleet experienced high employee turnover, and it's possible that these data reflect inaccurate record keeping.

demonstration. Removing the head revealed that three cylinders were oil-fouled, with the fouling in No. 6 being much worse than the other two cylinders. To insure that all six cylinders would be put in proper condition, all rings and cylinder liners were replaced.

In addition, during servicing of the cylinder kits, the oil control ring on cylinder No. 6 was found to be kinked. This was likely the result of a manufacturing defect, and would account for the high oil consumption rates for Tractor #1 that were observed during its 47,000 miles of demonstration. This problem was corrected, after which Tractor #1 exhibited a much lower oil consumption rate.

During the second, Commission-funded phase of the demonstration, JBK personnel continued to collect oil consumption data. However, as a result of employee turnover at the Fontana depot, ADLittle was not receiving reliable data. To fill this gap, JBK's director of maintenance supplied as much oil consumption data as available from corporate records for its entire Class 8 tractor fleet, including an average oil consumption value for JBK's extensive fleet of diesel tractors equipped with the Cummins M11 engine. As Figure 3-15 indicates, on average the three LNG tractors achieved 1,250 miles per quart of makeup oil – a vast improvement over the excessive oil consumption of LNG Tractor #1 before its ring-repair job. However, this represents about 33% and 62% fewer miles per quart of makeup oil than measured for the two diesel-engine references (the control tractor with a S60 diesel engine, and the average of JBK's diesel M11-equipped fleet, respectively).



**Figure 3-15. Average Oil Consumption Rates during Demonstration**

The trend illustrated in this figure highlights a common complaint from JBK personnel during the demonstration. Key JBK personnel voiced the concern that oil consumption for both the diesel and natural gas versions of the Series 60 engine are too high. To some extent, DDC and VDDA personnel acknowledged this phenomenon. In mid 2001, ADLittle checked with Vons Groceries (Santa Fe Springs, CA) to assess if the oil consumption levels of its new (essentially production) Series 60G LNG engines were high compared to its diesel fleet. Vons personnel

indicated that detailed records were not kept, but they had not noticed unusually high oil consumption for their fleet of 13 Series 60G-equipped LNG tractors.<sup>20</sup>

### 3.2.7.5 Routine Maintenance

JBK personnel periodically conducted routine maintenance on the three LNG tractors during the demonstration. When it became apparent that documentation by JBK maintenance personnel was somewhat marginal (August 1999, before LNG Tractors #2 and #3 were deployed), ADLittle and VDDA approached local JBK personnel about the prospect of VDDA performing routine maintenance. VDDA's offer was to perform all maintenance for the same price as JBK's cost to perform the maintenance. This made sense because VDDA was better equipped to service LNG systems, and could also provide better maintenance records to the project. However, JBK declined this offer due to the logistical difficulty of transporting LNG tractors between the two locations.

The following tables provide summaries of performance issues or maintenance events, and how they were resolved.

**Table 3-7. Examples of selected maintenance issues and solutions for Tractor #1**

<b>Date of Incident</b>	<b>Performance Issue / Maintenance Event</b>	<b>Solution / Work Performed</b>
11/22/99	Truck will not pull load. Driver noted low fuel pressure at engine gauge, but high pressure at tanks.	ADL discussed problem with JBK personnel. Agreed that in-line fuel filter may be clogged. Requested a replacement filter from VDDA.
12/15/99	Spark plug in Cylinder #6 showed oil fouling. Truck sent to VDDA for inspection and repair.	VDDA inspected other cylinders and found oil fouling in Cylinders 1 and 3. Replacement cylinder kits, head and oil pan installed.
01/14/00	Modifications required to comply with Title 13. Work performed while truck still at VDDA.	Methane sensor relocated to cab interior. Heat shield between tank and exhaust line is fabricated and installed by JBK.
04/27/00	Turbocharger failed, allowing oil entry into Cylinder #5.	VDDA replaced the cylinder kit and all main bearings and sent air to air aftercooler out to be cleaned. Turbocharger replaced.
10/11/00	Various problems with truck. In need of inspection and overhaul.	Major maintenance overhaul performed by VDDA

<sup>20</sup> Personal communication, Vons shop foreman Bob Schraeder to Robb Barnitt, ADLittle.

**Table 3-8. Examples of selected maintenance issues and solutions for Tractor #2**

<b>Date of Incident</b>	<b>Performance Issue / Maintenance Event</b>	<b>Solution / Work Performed</b>
12/13/99	Truck ran out of fuel.	Towed from Terminal 17 to UPS fueling station.
12/15/99	Driver reported misfiring, low fuel pressure and low power.	Appeared to be losing fuel pressure because economizer regulator was set too low. ALT personnel made regulator adjustment.
02/09/00	JBK driver reports engine cutting out.	DDC and ADL personnel made site visit to JBK terminal. A new certified calibration was downloaded. Recommended JBK set the fuel pressure to 120 rather than 150 psi. Truck sent to VDDA for spark plug re-gapping and intake/exhaust valve adjustment.
04/25/00	Truck misfiring.	DDC sent new oxygen sensor and regulator to VDDA, which completed installation.
10/11/00	Various problems with truck. In need of inspection and overhaul.	Major maintenance overhaul performed by VDDA

**Table 3-9. Examples of selected maintenance issues and solutions for Tractor #3**

<b>Date of Incident</b>	<b>Performance Issue / Maintenance Event</b>	<b>Solution / Work Performed</b>
11/08/99	Driver reports low power and rough operation. Sent to VDDA for service.	VDDA found and replaced cracked spark plug on Cylinder # 6.
12/15/99	Driver reported misfiring, low fuel pressure and low power.	Appeared to be losing fuel pressure because economizer regulator was set too low. ALT personnel made regulator adjustment.
02/09/00	Driver reports check engine light on.	DDC personnel re-calibrated to allow throttle to open more.
03/06/00	Engine missing, low power.	VDDA installed new regulator and PSV. ECM recalibrated.
10/11/00	Various problems with truck. In need of inspection and overhaul.	Major maintenance overhaul performed by VDDA

**Table 3-10. Examples of selected maintenance issues and solutions for the Diesel Control**

<b>Date of Incident</b>	<b>Performance Issue / Maintenance Event</b>	<b>Solution / Work Performed</b>
12/01/99	Preventative maintenance.	Replace alternator belts
12/22/99	Tank damaged by an object on the road.	Patch and weld left side fuel tank.
01/04/00	Road call.	Replace alternator on the road.
01/22/00	Water pump failure.	Remove and replace water pump and hoses.
03/02/01	Preventative maintenance.	Replaced #4 radiator hose, horn, front brakes, antennas kit

In general, the diesel control truck required significantly less maintenance, as compared to the LNG trucks. Much, but not all, of the maintenance events for the LNG tractors were specific to the prototype LNG-fueled engine and on-board LNG fuel system. To some extent, this is to be expected during demonstration and road testing of an essentially prototype technology.

### **3.2.7.6 Road Calls**

No emergency road calls were documented by JBK during the initial 47,000+ mile demonstration of Tractor #1. Driveability problems were documented that required remedial action during subsequent service calls, however. Aside from the downtime associated with fixing the oil consumption problem (discussed in Section 3.2.7.4), the only incidents that impeded operation were a faulty sensor that caused occasional engine faults and shutdowns in April 1990, and a clogged fuel filter in November 1999.

During the Commission-funded demonstration of all three LNG tractors that followed, incidents did occur that required road calls. Often, these were related to “out-of-fuel” situations that remain somewhat common with LNG vehicles in trucking applications, due to limited range, the current limited numbers of fueling stations, and other factors described further in this report.

### **3.2.7.7 Driveability and Performance**

As previously noted, during checkout testing of LNG Tractors #2 and #3, driveability problems were found to be associated with low fuel pressure (60-70 psi) to the engines. This pressure was below both the engine specification and the actual tank pressure. DDC and VDDA addressed these early driveability problems associated with low fuel pressure, by adjusting the economizer valve and final line regulator and clearing out fuel lines for potential obstructions.

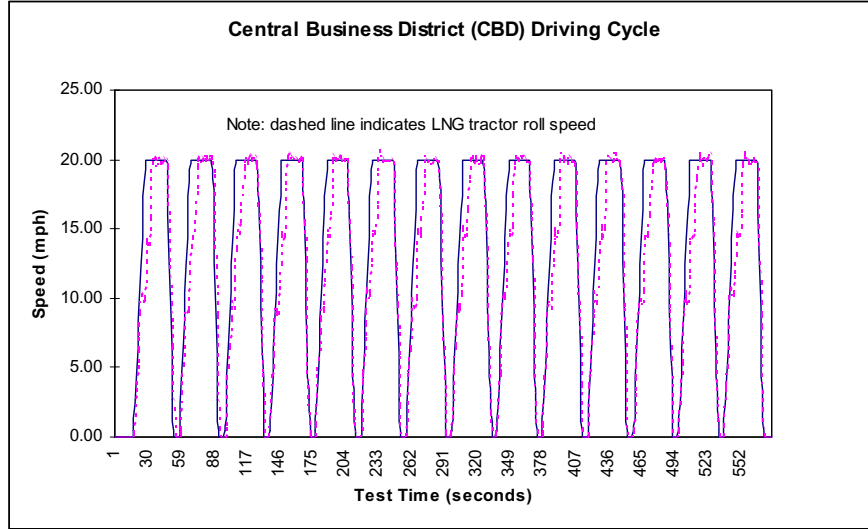
Once the LNG tractors were put in service with JBK, driver input was used as a key factor in identifying problems and assessing commercial viability of the new 400-hp S60G engine. The general practice used by JBK at its Fontana depot is to assign multiple drivers to its various diesel-fueled tractors. For the LNG tractor demonstration, a different system was set up. In the interest of minimizing variability and maximizing safety and data collection effectiveness, JBK assigned a select few drivers to operate the LNG tractor and the diesel control tractors. For example, the primary driver that was selected for Tractor #1 and used throughout its initial 12-month demonstration had previously operated an LNG tractor equipped with the Caterpillar /

Power Systems dual-fuel engine. This system of using the best-fit drivers was followed as much as possible without negatively impacting JBK's normal operations and driver rotation system. However, as described in various sections of this report, high turnover among drivers at the Fontana fleet ultimately hindered continuity of use.

During the course of the demonstration for the three LNG tractors, ADLittle collected driveability input from the drivers via site visits, phone calls and inspection of the driver's log kept in each truck. The drivers generally expressed satisfaction with the LNG tractors' performance, especially in comparison to a dual-fuel tractor equipped with the early-generation 3126 Caterpillar engine (250 HP @2200 rpm, 660 lbs-ft @ 1440 rpm), which some of the drivers had previously test driven. One negative comment was that the LNG tractors required extra time to fuel compared to a typical diesel tractor (discussed further under Task 3 – LNG Fueling). Table 3-2 summarizes feedback from JBK drivers on the LNG tractors.

Perhaps the most significant dissatisfaction among JBK personnel occurred in early Q4, 2000, when the drivers reported that none of the three LNG trucks were running properly. To troubleshoot the problem, in early October 2000 DDC's John McNeill made the first of several trips to VDDA. The objective was to inspect the LNG trucks and assess the need for repair and replacement of parts. ADLittle personnel made site visits to VDDA on October 11th and 12th, and November 2nd to meet with Mr. McNeill, join him in assessing the condition of the trucks, and obtain photo documentation of repair actions. The resulting major maintenance events are described for each tractor in Section 3.2.7.5.

ADLittle also received feedback from the California Truck Testing Services (CaTTS) laboratory about driveability of one LNG tractor during chassis dynamometer emissions testing (see page 3-34 for details about emissions). The CaTTS technician drove the LNG tractor extensively on the dynamometer, following three different driving cycles (Modified CBD, Commuter, and UDDS). He noted that the engine had good power and torque compared to a similar diesel engine, but he found the driveability to be hindered somewhat by a transmission poorly matched with the DDC Series 60G engine. Figure 3-16 shows the speed versus time trace of the Modified Central Business District cycle (CBD), compared to the dynamometer roll speed of the LNG tractor during testing (dashed line). This graph shows that the LNG truck was able to provide the hard accelerations required by the test cycle, but the dashed line (tractor roll speed) is also indicative of the shifting problem noted by the driver. Table 3-11 provides a summary of the driver's observations about the shifting problem.



**Figure 3-16. Acceleration of LNG Tractor during CBD cycle at CaTTS**

**Table 3-11. Comments of CaTTS driver on LNG tractor driveability.**

1. Accelerator lag doesn't allow the engine to slow to the speed necessary to synchronize with the next higher gear.
2. Rockwell 10-speed manual transmission is geared low in the first 3 gear positions with large "gaps" between 3-4 and 4-5.
3. The above two conditions made it difficult to follow a driving trace, because momentum is lost waiting for the engine speed to slow to the next synchronized point. The first condition affected CBD cycle testing, while the second affected the Commuter and UDDS cycles.
4. Similarly, the reverse of this situation precludes downshifting, which places additional strain on the brakes.

While these driveability problems did occur, it is important to stress that the technological advancement for this project involved the upgraded Series 60G engine and not the tractor itself. Future commercialization of the engine will be with an optimized chassis, transmission and on-board fuel system. In fact, that process has begun with the recent deployment of up to 32 International Class 8 LNG trucks with the newly certified, upgraded version of the Series 60G engine at Vons and Albertson's grocery chains.

### 3.2.7.8 On-Board LNG Fuel System

On-board storage of LNG is accomplished with double-walled stainless steel cryogenic tanks that are "superinsulated" to prevent heat transfer into the tank from outside sources.<sup>21</sup> The three demonstration LNG tractors were equipped with on-board LNG tanks and systems from MVE<sup>22</sup>

<sup>21</sup> In an LNG tank, an outer tank encloses the inner tank, and vacuum is drawn between the walls, creating an effect called "superinsulation."

<sup>22</sup> After the project began, MVE became part of Chart Industries. In late 2001, Chart renamed its LNG fueling division "NexGen Fueling."

that were already several years old, by the time they were purchased from LCI and delivered to VDDA for engine upgrades. For this reason and because the tractors had not been used significantly for several years, ADLittle and its subcontractors performed checkout testing of each MVE system upon tractor delivery to VDDA. At the time each vehicle was received, all systems were shown to be functional, and it was concluded that no major work was needed to return the system to operation.

During the course of the demonstration, these LNG systems initially performed well despite not being “state of the art” or optimally functional. For example, these MVE systems had not been designed for single point refueling of both LNG tanks (i.e., there was no functional crossover link between the two tanks). This required the JBK drivers to turn each truck around to facilitate refueling of both tanks, because the refueling connections at the Ontario LNG station were not long enough otherwise. Since the Ontario station was slated for a major upgrade under GRI and SCAQMD funding (see section 3.4.2), it was not cost-effective to install longer fueling connections at the station as an interim measure.

Periodically throughout the two-phased demonstration, ADLittle and its subcontractors performed minor upgrades to the LNG tractors’ fuel systems. These upgrades included replacing clogged in-line fuel filters, replacing pressure relief valves to correct faulty venting, and installing MVE excess flow check valves and Parker LNG fill receptacle covers to comply with California Title 13.

As discussed previously, major maintenance overhauls were performed by DDC and VDDA on each LNG tractor in late 2000 / early 2001. During this procedure, the condition of each on-board LNG fuel system was re-assessed. From this process, it became apparent that upgrading or replacing the LNG tanks and fueling systems could significantly improve the performance and utilization rate of the JBK trucks for the remaining portion of the demonstration. Knowing that the project budget was insufficient to pay for fuel system upgrades, ADLittle contacted JBK CEO Ken Kelley, who agreed that JBK would pay the costs of refurbishing the six LNG tanks. Chart-MVE agreed to cost share this work by performing all LNG tank upgrades at its own cost (i.e., zero markup).

Beginning in early 2001, The six LNG tanks were shipped back to the Chart-MVE facility in Canton, Georgia. The procedure included refurbishing the tanks and replacing all tank-connected hardware. Being external to the tank and located on the fuel line to the engine, LNG vaporizers (heat exchangers) were not included in this process; however, all three were working satisfactorily.<sup>23</sup> Specific work in the tank refurbishment process included the following:

1. Cutting open each of the tanks, and scraping residue from the interior vessel walls<sup>24</sup>
2. Resealing the tank, and restoring the vacuum condition required to minimize heat leak

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<sup>23</sup> As previously noted, the existing LNG vaporizers were originally deemed adequate for the upgraded, higher-horsepower S60G engines, in part because budget did not exist to replace them. It is possible that driveability issues encountered by JBK during the field demonstration were directly related to vaporizer overloading.

<sup>24</sup> The source of this residue could not be pinpointed. DDC analyzed the material at their in-house laboratory, and determined it to be carbon.

3. Replacement of all tubing and valves connected to the tank, including:

- Fill connector
- Fill check valve
- Primary relief valve
- Secondary relief valve
- Secondary relief valve pressure gauge
- Vent valve
- Economizer regulator

4. Replacement of fill connectors and caps<sup>25</sup>



**Figure 3-17. Refurbished (by Chart) LNG tank, reinstalled on Tractor #2.**

The six LNG tanks were refurbished by Chart-MVE and returned to VDDA on a staggered schedule. Upon arrival at VDDA, the tanks were re-installed on the corresponding tractor, which was then fueled and run on a dynamometer for checkout testing. Table 3-12 presents the schedule of tank return, truck availability to JBK, initial problems experienced by the trucks, and how those problems were resolved.

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<sup>25</sup> Initially, fill connectors were not replaced by Chart-MVE, but leakage at the connectors occurred upon return of the tanks and refueling of the trucks. Chart-MVE subsequently shipped replacement fill nozzles to VDDA for installation.

**Table 3-12. Timeline for LNG Tank Refurbishing and Return of Trucks to Service**

<b>Activity</b>	<b>LNG Truck #1</b>	<b>LNG Truck #2</b>	<b>LNG Truck #3</b>
Date LNG tanks sent to Chart-MVE	<b>1/29/01</b>	<b>1/31/01</b>	<b>3/22/01</b>
Post-return adjustments performed on trucks by VDDA and JBK	<ul style="list-style-type: none"> <li>Replaced tires and mirrors</li> </ul>	<ul style="list-style-type: none"> <li>Replaced low pressure regulator (part warranty)</li> <li>Replaced valve cover base</li> </ul>	<ul style="list-style-type: none"> <li>None reported</li> </ul>
Date truck available to JBK for regular use	<b>3/6/01</b>	<b>3/6/01</b>	<b>4/2/01</b>
Performance comments since return to use	<ul style="list-style-type: none"> <li>Lope while idling</li> </ul>	<ul style="list-style-type: none"> <li>Lope while idling</li> <li>Methane detector false positive (self rectified)</li> </ul>	<ul style="list-style-type: none"> <li>Lope while idling</li> </ul>
Additional corrective action taken	<ul style="list-style-type: none"> <li>DDC/VDDA uploaded air/fuel ratio lookup table data to ECM</li> </ul>	<ul style="list-style-type: none"> <li>DDC/VDDA uploaded air/fuel ratio lookup table data to ECM</li> </ul>	<ul style="list-style-type: none"> <li>DDC/VDDA uploaded air/fuel ratio lookup table data to ECM</li> </ul>

One problem that came to light during the demonstration was the difficult logistics of servicing on-board LNG fuel systems at a location not equipped for onsite LNG fueling. For example, when ADLittle and VDDA removed and replaced fuel system hardware on Tractor #1 in late 1999, all onboard LNG fuel had to be vented first. In addition to the loss of valuable fuel, this required towing the tractor to the Ontario station (approximately 25 miles one way) when the work was completed. Similarly, when the three LNG tractors were parked for extended periods at VDDA awaiting parts and service, they lost enough fuel through boil off to require towing to the Ontario station. This fuel-system-related limitation – coupled with the problem of a very limited LNG station infrastructure – highlights a significant current barrier for wider deployment of LNG-fueled vehicles. Mobile fueling of LNG trucks is a potential interim solution, but it is not widely practiced or economical due to the current paucity of LNG vehicles.

### **3.2.8 Subtask 1.7 – LNG Training**

Shortly after the engine upgrade was completed on Tractor #1 and it was delivered to JBK, ADLittle joined with DDC to implement a training session at JBK's Fontana depot. Topics covered included LNG properties, safety, fueling procedures, and environmental benefits. Attending for JBK were drivers, maintenance personnel, and depot managers. This work was performed under the SCAQMD and DOE/NREL portion of the project.

Due to high turnover at JBK's Fontana depot (including depot managers, drivers and mechanics), ADLittle organized and implemented a second training session on April 9-10, 2001. This work was performed under the Commission-funded part of the project, with cofunding by the AB 2766 Mobile Source Air Pollution Reduction Review Committee (MSRC) under its Technical Assistance to Heavy-Duty Fleets contract. The course was taught at the JBK Fontana depot by Laks DeSilva, training manager for VDDA. Topics again included LNG properties, safety, fueling procedures, and environmental benefits. JBK personnel who attended included maintenance personnel, mechanics, and depot managers.



**Figure 3-18. VDDA instructor during April 2001 LNG training at JBK**

### **3.2.9 Special Events and Workshops**

During the SCAQMD and DOE/NREL portion of the project, Tractor #1 was exhibited at several AFV workshops and special events. These events served to educate decision-makers and the general public about opportunities for clean transportation. ADLittle arranged for the vehicle to be delivered to the workshops, prepared literature on the project for displays, and attended the workshops to answer questions. Driver delivery costs for the events were paid by project funding or provided as a cost share by JBK. Table 3-13 provides a summary of the events where Tractor #1 was displayed. Tractors #2 and #3 were not displayed at such special events, although #3 was sent to Northern California for chassis dynamometer emissions testing (see Section 3.3.2).

**Table 3-13. Displays of Tractor #1 During Special Events and Workshops.**

<b>Event or Workshop and Location</b>	<b>Date(s)</b>	<b>Purpose / Target Audience</b>
SoCalGas Natural Gas Vehicle Expo, Downey, CA	April 7 – 8, 1999	Display truck to prospective fleet users and chassis OEMs, including Freightliner, Ryder, ACE Hardware, and Harris Ranch
Freightliner's AFV BBQ Luncheon, Whittier, CA	May 13, 1999	Display truck to potential fleet users (Freightliner considering commercial potential).
Pacific Gas & Electric Natural Gas Vehicle Expo, San Ramon, CA	June 23, 1999	Display truck to Northern California fleet users.
SCAQMD Environmental Reporter Conference, Diamond Bar, CA	September 16, 1999	Display truck to environmental reporters for SCAQMD.

### 3.3 TASK 2 — EMISSIONS TESTING

One of the key objectives of the project was to expedite commercial introduction of the upgraded, high performance DDC Series 60 natural gas engine by 1) achieving emissions certification in California, and 2) obtaining chassis dynamometer emissions data to corroborate its low-emissions potential in real-world use. Both objectives were achieved, as described below.

#### 3.3.1 Certification Testing

The 400 horsepower version of the DDC Series 60G natural gas engine successfully completed emissions testing at Southwest Research Institute in December 1999. DDC submitted the results to both EPA and ARB in late January 2000, with a request for certification via a running change from the previously certified 330-hp version. Table 3-14 shows the results of the certification testing with an emission data engine at SwRI.

**Table 3-14. Certification test results at SwRI for the 400 HP DDC S60G natural gas engine.**

Exhaust Emissions Test	MAX TORQUE (lb-ft)	RATING (hp @ rpm)	BSNO <sub>x</sub> (g/bhp-h)	BSNMHC (g/bhp-h)	BSCO (g/bhp-h)	BSPM (g/bhp-h)
Federal Test Procedure	1450	400@2100	1.95	0.51	1.79	0.010



**Figure 3-19. Detroit Diesel Series 60G engine. Photo courtesy of DDC.**

A summary of the activities by DDC and ADLittle during this process to certify the 400 horsepower LNG-fueled Series 60G engine in California is provided in Table 3-15.

**Table 3-15. Chronology of emissions certification process for the 400-hp DDC S60G LNG engine**

Month	Event / Work Performed
Sep '98	DDC completes 49-State certification of the 330-hp version of the upgraded S60G engine for CNG applications only. The results (without an oxidation catalyst) indicate upgraded engine will meet California's Optional Low-NOx Emission Credit Standards.
Oct '98	ADLittle works with DDC to preliminarily assess the potential to certify the LNG version of the upgraded S60G engine.
Jan '99	DDC reports that its application for California certification is under evaluation by ARB. DDC also confirms that the engine was certified to the conventional 4.0g/bhp hr NOx standard, and not to an optional low-emission standard.  DDC assesses the market demand for a 400-hp version of the S60G for the trucking market. ADLittle and gov't sponsors stress that a low-NOx certification of the engine could result in significant demand through its eligibility for Carl Moyer program funding and other incentives.
Feb '99	ADLittle reviews DDC's preliminary certification for the urban bus engine.  ADLittle follows up with DDC about certifying the 400-hp LNG truck engine.
April '99	ADLittle assembles additional information for DDC about benefits of certification to optional low-NOx standard, including financial incentives for users.  ARB Certification engineer writes to ADLittle, citing <b>Executive Order A-290-72</b> to verify that Series 60G is certified as CNG-only bus or truck engine (no engine family identified). To obtain LNG certification, ARB cites need for DDC to demonstrate "fuel system components as regards low-temperature exposure or avoidance of liquid-lock."
July '99	DDC reports that it will apply for certification for the 330-hp LNG S60G in tandem with the 275-hp LNG S50G. DDC schedules certification emissions testing at SWRI.
Aug '99	ADLittle investigates status of DDC progress through discussions with relevant parties and prepares a detailed written update for SCAQMD, CEC, and NREL.
Sept '99	ADLittle contacts DDC to confirm that plans are on track to emissions test the 400-hp engine at SWRI in early October.
Nov '99	DDC confirms that the 400-hp S60G LNG engine had been installed in a test cell at SWRI with testing scheduled to begin in December.
Dec '99	DDC reports that the S60G LNG engine completed testing at SWRI.
Jan '00	DDC submits certification reports to EPA and CARB, with running change request.  ARB signs <b>Executive Order A-290-87</b> , verifying that the 2000 MY S60G engine (Engine Family <b>YDDXH12.7FGF</b> ) has been certified on either CNG or LNG. NOx is at 4.0, so E.O. does not indicate compliance with optional low-NOx credit standard. Urban buses are the only application noted. No Engine Codes or engine HP / Torque ratings are provided.
Feb '00	DDC submits 2000 Running Change Number 03, requesting addition of Engine Code 979 (LNG-fueled 400 HP / 1450 lbs-ft.) to S60G Executive Order.  DDC downloads ECM program (R-27) and calibrations from the SwRI test to the three JBK trucks, with field assistance from ADLittle. Driveability problems are documented and addressed. New valves, regulators, and oxygen sensors are ordered.
Mar '00	DDC and VDDA install the new valves and regulators and adjust all three trucks to the new calibration. Fuel regulator compatibility issues with new ECM program and calibrations are addressed (see 3.2.5 for discussion). Tractor #1 is tested on the VDDA chassis dynamometer and performance is documented.

Table 3-15 (Continued)	
Jul '00	ARB Certification engineer tells ADLittle that “engine manufacturer must still be responsible for LNG fuel system” of certified LNG-fueled HDVs. He cites the inability of on-board fuel system manufacturer to take financial responsibility.
Oct '00	ARB Certification engineer sends e-mail to ADLittle confirming that DDC has submitted a running change request for <b>Engine Family YDDXH12.7FGG</b> (2.5 gram NOx version of the S60G), for urban buses on CNG or LNG. No further concerns about fuel system issues are cited.
Jan. '01	ARB signs <b>Executive Order A-290-98</b> , verifying that the 2001 S60G engine ( <b>Engine Family 1DDXH12.7FGG</b> ) has been certified on either CNG or LNG to California’s Optional Low-NOx Emission Credit Standards. Urban buses are the only application noted. However, EO attachment indicates that Engine Codes 978 and 1371 are rated at 400 HP @ 2100 / 1450 lbs-ft @ 1200.
Jan. '02	ARB website lists 2001 MY S60G as certified to California’s Optional Low-NOx Emission Credit Standards for both CNG and LNG, in urban bus (330 HP) or heavy-duty truck (400 HP) applications. No 2002 MY data are posted yet.



**Figure 3-20. VDDA technician changing regulator after re-installing R27 program**

As previously described (see Section 3.2.5.1), one of the upgrades that DDC performed during the project was to install the R27 ECM program and a new calibration. In early 2000, DDC and VDDA collaborated to fix low-pressure regulator problems on each of the three LNG tractors,

which were exacerbated by the new calibration. ADLittle staff spent extensive time at the site during these repairs, to document the work and take photographs.



**Figure 3-21. Roger Parry (DDC) completing download of R27 program.**

As a result of this certification, the 400-HP S60G LNG engine has been moved closer to sustainable commercialization in heavy-duty trucking applications. In January 2002, the engine was finally acknowledged on the Air Resources Board website as being certified to California's Optional Low-NOx Emission Credit Standards. Activities carried out under the Commission-funded project played a significant role in obtaining this low-NOx certification and its recognition. For nearly a year after ARB issued DDC Executive Order A-290-98 (see Table 3-15 describing the chronology of the certification process), only the 330-HP version of the Series 60G engine (for over-the-road coach applications) was listed on ARB's website as being certified to California's Optional NOx Emission Credit Standards. Repeated inquiries by Commission and ADLittle staff to ARB and DDC were instrumental in finally rectifying this apparent oversight. As a result, with the S60G now officially recognized as achieving the special standard, fleets can receive funds for deployment of the 400-HP S60G engine under the Carl Moyer program or other similar incentive programs.

### **3.3.2 Chassis Dynamometer Emissions Testing**

Another important part of Task 2 called for ADLittle and DDC to help facilitate chassis dynamometer emissions testing of a JBK tractor with the upgraded DDC S60G engine. While the actual emissions testing was beyond the project's budget, a key goal was to seek and procure testing under another source of funding, as a cost share to the project. One option was to conduct the testing at the emissions test facility at the Los Angeles County Metropolitan Transit Authority (LACMTA), under an arrangement between SCAQMD and the facility operators. However, the LACMTA lab was not available for testing during the term of the project. Thus, as the project

progressed, ADLittle investigated alternative options for chassis emissions testing at other facilities.

In late 1999, ADLittle had discussions with Pacific Gas & Electric (PG&E), which was interested in emissions testing a tractor with the upgraded DDC S60G engine at the California Truck Testing Services (CaTTS) laboratory. This was part of PG&E's program to assess the effect on NOx emissions of various non-methane components commonly found in CNG fuel (e.g., ethane, propane). As an incentive, PG&E and CaTTS agreed to include testing on the as-received LNG fuel. ADLittle agreed to discuss the issue with DDC and seek permission to conduct the testing. However, a potential problem was that none of the three LNG tractors in the JBK fleet had accumulated sufficient mileage after engine work to achieve proper break in. This raised concern that the particulate and hydrocarbon emissions might not be representative of a properly broken-in engine. DDC and ADLittle discussed the issue with PG&E, and it was noted that the test methodology was focused on NOx emissions as a function of fuel quality. PG&E intended to report data only by generic engine information (e.g., "Engine A"). Thus, DDC and ADLittle agreed that this free chassis dyno testing at CaTTS offered no down side, and should proceed as soon as sufficient engine break-in was achieved on one of the three JBK trucks.

In March 2000, final arrangements were made between CaTTS, ADLittle and JBK to deliver one of the LNG tractors to the CaTTS laboratory. Tractor #3 (JBK fleet #70) was chosen for the testing because it was available at the time, and operating well. A CaTTS staff member flew down from Oakland to Ontario Airport, where ADLittle staff picked him up. Next, they met the JBK driver with Tractor #3 at the Ontario LNG station, where it was fueled. That same day, the CaTTS staff member drove Tractor #3 to the CaTTS laboratory in Richmond (near Oakland), refueling along the way at the Harris Ranch LNG station.

While at the CaTTS laboratory, Tractor #3 was emissions tested on both LNG and CNG fuel, using multiple test cycles. For LNG testing, the test matrix included four different driving cycles on the tractor with its "as-received" fuel. Driving profiles ranged from the Central Business District (CBD) cycle with hard accelerations, to the Commuter cycle consisting primarily of a single, four-minute cruise at 50 mph. Other tests that were conducted included the Modified Central Business Cycle (MCBD) and the Urban Dynamometer Driving Schedule.

Emissions levels during the CaTTS testing of Tractor #3 exhibited high variability over the various test cycles, in part due to the lack of engine break-in miles. NOx levels over the CBD cycle ranged from 2.7 grams per mile to 8.6 grams per mile. Particulate matter emissions were not finalized but were higher than might be expected from a natural gas engine. This is also probably attributable to lack of break-in miles.

Obtaining an "apples-to-apples" comparison of emissions from the S60G-powered LNG tractor to a conventional tractor with the S60 diesel engine was not possible at the time this report was written. However, limited data were available to compare a tractor powered by a DDC Series 50 diesel engine under the same test cycle. The Series 50 engine is a 315-HP, four-cylinder version of the six-cylinder Series 60 engine, with the same production parts. It is a reasonable surrogate for the Series 60 diesel, in terms of emissions.<sup>26</sup> Table 3-16 lists the averaged NOx emissions

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<sup>26</sup> However, caution is needed in making such comparisons. Numerous vehicle and test-procedure variables may have existed, for which details are not available.

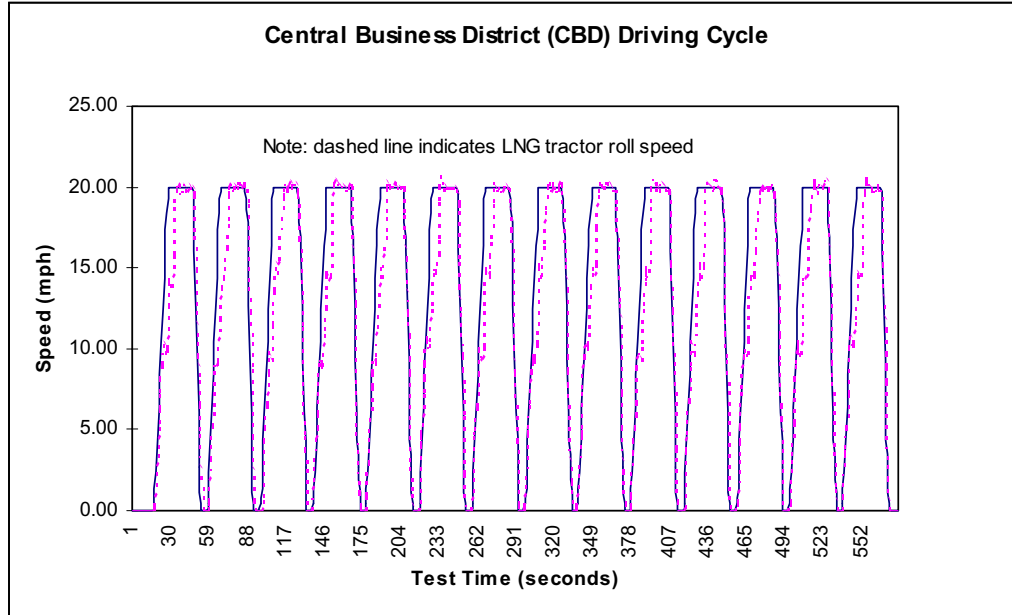
from the Series 60G-equipped LNG tractor and a tractor with a 1997 DDC Series 50 diesel engine, over the Central Business District (CBD) test cycle. Figure 3-23 shows the speed versus time trace of the CBD and the (dyno roll) speed of the LNG tractor during one of the tests.



**Figure 3-22. LNG Tractor #3 during CaTTS emissions testing (photo courtesy of CaTTS)**

**Table 3-16. Comparison of NO<sub>x</sub> emissions from diesel and LNG tractors tested at CaTTS over the Central Business District (CBD) Test Cycle**

Test Vehicle	Engine / Fuel	Test Fuel	NO <sub>x</sub> (g/mile)
1986 GMC	'97 DDC Series 50	Diesel #2	27.4
1995 Freightliner FLD 120 (LNG Tractor #3)	Upgraded '95 DDC S60G	LNG	7.2
Testing for the LNG tractor was conducted at CaTTS on April 10, 2000. Testing for the diesel tractor was conducted at CaTTS on March 17, 1999. Certain test parameters (e.g., inertia mass, road load) and vehicle details were not available. NO <sub>x</sub> data are the average of 3 tests for both vehicles. Particulate data were not available.			



**Figure 3-23. Roll speed of LNG tractor over CBD test cycle during CaTTS testing.**

In general, the CaTTS testing on LNG Tractor #3 further corroborates the well-documented capability of heavy-duty natural gas engines to emit at least 50% less NO<sub>x</sub> than comparable diesel engines. However, the most important measure of the Series 60G emissions benefits will be future in-use emissions testing after the engine is commercially deployed in purpose-built LNG truck chassis, with state-of-the-art onboard fuel systems, compatible transmissions, etc.

### **3.4 TASK 3 — LNG FUELING (Non-Commission Funding)**

While Task 3 was not part of the Commission-funded effort, it served an important role in the overall cost-shared program to demonstrate three Class 8 LNG tractors. This task essentially consisted of various efforts by ADLittle and the LNG fuel providers to support the LNG fueling needs of the JBK LNG fleet and other heavy-duty fleets using LNG.

#### **3.4.1 SCAQMD's Support of the Downtown Los Angeles LNG Station**

One major part of Task 3, which was performed 100% under SCAQMD funding, was to provide financial support for the Downtown Los Angeles LNG station. Specifically, ADLittle worked with SCAQMD staff, Mesa Pacific LNG, and Cryogenics R&D to arrange to keep the station open for approximately one year longer than it would otherwise have been operational. The hope was that this would help the station survive its early low throughput problems and eventually become self-sustaining, as more LNG vehicles were deployed.



**Figure 3-24. The Downtown Los Angeles Mesa Pacific LNG Station**

#### **3.4.2 GTI and SCAQMD's Support for Upgrades to the Ontario L/CNG Station**

The primary fueling station for the three LNG tractors was the ALT USA facility located on the property of United Parcel Services at 1735 S. Turner Avenue in Ontario, California. ALT-USA owns and maintains this station. It was constructed in 1996 with funding from the San Bernardino Association of Governments (SANBAG) and SCAQMD. Some of the funding was provided through contracts with ADLittle in a previous project. LNG fueling at the station began in March of 1998. This station includes an L/CNG facility that supplies CNG to UPS and the general public.<sup>27</sup> LNG users have included JBK, UPS, ACE Hardware, and Con-Way Express,

<sup>27</sup> An L/CNG station pumps methane from the bulk LNG tank up to high pressure and vaporizes it at CNG pressure.

among other heavy-duty fleets. The original design features of the station are described in Table 3-17.

**Table 3-17. Original design features of the Ontario UPS L/CNG fueling station.**

Feature	Description
LNG storage tank	6,000 gallon double-walled, vacuum-insulated storage vessel, manufactured in 1995 by Minnesota Valley Engineering (Model HLNG-6000-NC-250). Insulated to achieve a normal evaporation rate less than 0.35% of tank capacity per day. Equipped with pressure building coils for bulk conditioning of contents to desired saturation pressure. Rated for a maximum working pressure of 250 psig.
LNG leak containment	A concrete block wall surrounds concrete tank pad. Volume of the enclosure is sufficient to hold the tank's capacity of 6,000 gallons.
LNG dispensing pump	Single stage centrifugal pump, manufactured by ACD. Pump is rated to deliver 30 gpm with a pressure rise across the pump of 60 psi. Pump is driven by a 7.5-hp, 460V AC, 3-phase motor.
LNG flow totalizing	Micro-motion vibrating tube mass flow rate gauge
LNG dispensing nozzle	Parker-Hannefin Model 1169-60B
Vapor return nozzle	MVE
LNG control valves	Solenoid controlled, air actuated, manufactured by ACD. Service air is provided by a mechanical compressor located in the shed housing the site controller and water heater.

Source: Drexel LNG & CNG Systems, "Data Package for ALT/UPS LNG /LCNG Vehicle Fueling Facility, Ontario, California." June 1, 1997.

During the first several years of its operation, as increasing numbers of LNG vehicles were deployed in the South Coast basin, it became apparent that the Ontario L/CNG station had several significant problems, including the following deficiencies<sup>28</sup>:

- The single-stage pump required too much time to cool down, and often had insufficient discharge pressure to support a single-hose top fill.
- The L/CNG pump was not reliable, and spare parts were not readily available.
- The LNG fill hose was substandard.
- The process piping arrangement did not allow simultaneous L/CNG and LNG fueling.
- The complex, proprietary control system was very difficult to maintain or modify.

In 2001, ALT-USA contracted with GTI and SCAQMD to upgrade the station. The focus of the upgrade was to replace the LNG pump, modify and optimize piping, and upgrade the control system. Specific changes included the following:

<sup>28</sup> Source: "Ontario, CA LNG and L/CNG Station Evaluation and Upgrade," GRI Proposal #98-475 from ALT-USA.

- A new two-stage, submerged duplex pump was installed to replace the original single-stage pump.
- The L/CNG triplex pump was replaced with a new duplex pump.
- Piping modifications were made to improve the performance and efficiency of the station.
- A revised control system was installed that offers ability to interface with a card reader system.
- The dispenser control system was upgraded to meet applicable weights and measures requirements of the California Department of Food and Agriculture, Division of Measurement Standards.

The Ontario L/CNG station was completed in mid 2001. Table 3-18 lists the total costs to perform the upgrades, and how the project was funded.

**Table 3-18. Funding sources for Ontario L/CNG station upgrade, completed in mid 2001**

<b>Funding Entity</b>	<b>Amount of Cost Share</b>
GTI (including grant funds from the South Coast AQMD)	\$75,000
Applied LNG Technologies USA, LLC	\$107,409
<b>Total Funding for Station Upgrade</b>	<b>\$182,409</b>
Source: Letter from Steve Bartlett, Applied LNG Technologies, to Jon Leonard, Arthur D. Little, July 12, 2001	

### 3.5 TASK 4 — REPORTING

The primary objectives of Task 4 were: 1) to provide progress reports to the Commission (as well as NREL and SCAQMD under the related projects); 2) to arrange periodic project review meetings or teleconferences as needed; 3) to provide real-time updates on project progress, and 4) prepare a final report at the project's conclusion.

Over the life of the two related projects, ADLittle prepared regular progress reports detailing the technical and fiscal status of the project. Initially, these were in the form of monthly progress reports, but the format was switched to quarterly progress reports to stretch Task 4 funds as far as possible. To ensure that Commission staff were kept informed on a more frequent basis, however, ADLittle provided regular and real-time updates in the form of memos, email messages and faxes.<sup>29</sup> Table 3-19 summarizes some of the key efforts and accomplishments under Task 4, excluding the normal preparation of progress reports.

<sup>29</sup> In general, ADLittle's direct labor to perform the work described in each update was charged to the related task, while the time to write up the report was charged to Task 4 – Reporting. This was efficient because the written topical report could then be applied to progress reports and the final report.

**Table 3-19. Examples of work performed by ADLittle  
under Task 4 (excluding progress reports)**

<b>Month</b>	<b>Work Performed</b>
Sep '98	Project kickoff meeting (1 <sup>st</sup> Quarterly Progress Review)
Jan '99	2 <sup>nd</sup> Quarterly Progress Review Meeting
Jul '99	3 <sup>rd</sup> Quarterly Progress Review Meeting
Aug '99	Memo: Inspection Report for LNG Tractors #2 and #3
Oct '99	Memo: Loss of Vacuum in LNG Tank for Tractor #3 Memo: Repairs Needed for (All 3) LNG Tractor Fuel Systems
Dec '99	Memo: 12-20-99 Site Visit to JBK and Activity Update
Jan '00	Initiated Draft Final Report
Feb '00	4 <sup>th</sup> Quarterly Progress Review Meeting
April '00	Submitted Draft Final Report for SCAQMD / NREL Project
May '00	Completed and submitted Final Report
June '00	Memo: Update on Emissions Certification and Status as Moyer Eligible Engine
Oct '00	Memo: 09-29-00 Site Visit to JBK and Activity Update Memo: 10-11-00 Site Visit to VDDA to Document Repairs
Nov '00	Memo: 11-02-00 Site Visit to VDDA (follow-up on VDDA Repairs)
June '01	Memo: 06-14-01 Site Visit to JBK
Feb '01	Memo: 02-01-01 Site Visit to JBK Memo: 02-21-01 Site Visit to JBK
Sept '01	Memo: 09-25-01 Site Visit to Vons (Collect Supplemental Data)

### **3.6 Follow-On Work and Statement of Future Intent**

With the completion of the project, Arthur D. Little ended its formal involvement with the JBK LNG truck demonstration. However, JBK continues to operate the LNG trucks and accumulate mileage, displacing usage of diesel fuel and providing significant reductions in NOx and diesel particulate emissions. DDC and its affiliate, Valley Detroit Diesel Allison, have offered to provide field support to JBK under normal payment procedures, and JBK has expressed interest in purchasing new S60G-equipped tractors. ADLittle will continue to work with JBK and Detroit Diesel Corporation to gain important knowledge of how Class 8 LNG trucks operate in real-world conditions. Such information and data will continue to assist in advancing the self-sustainable commercial viability of LNG in trucking applications.

There has been a very encouraging follow-on effort to the program described in this report. Two major grocery chains, Vons Groceries and Albertson's, Inc., are working with DDC and VDDA to deploy at least 32 new LNG tractors in their Southern California fleets. These tractors are equipped with the same high-horsepower, high-torque S60G engine developed under the

Commission / SCAQMD / DOE-NREL program. Figure 3-25 shows one of these new LNG tractors, refueling at the Vons Groceries LNG station in Santa Fe Springs.



**Figure 3-25. An LNG tractor with DDC S60G engine, refueling at Vons Groceries, Santa Fe Springs**

## **4. CONCLUSIONS AND RECOMMENDATIONS**

This demonstration marked the first use in California of dedicated natural gas semi-tractors with the high horsepower and torque needed to compete with conventional, diesel-powered tractors in Class 8 trucking applications. The project was successful as an important step towards full commercialization of dedicated LNG tractors with upgraded, low-NOx DDC Series 60G engines. Key project objectives and goals were met, although significant problems were encountered that resulted in fewer hours of vehicle operation and miles accumulated than originally anticipated.

Specific accomplishments, conclusions and recommendations from this project are summarized below, by various categories.

### **4.1 LNG Engine Technology and Commercial Viability**

- The upgraded S60G engine in the first LNG tractor (#1) performed extremely well over the first nine months of the demonstration. The only significant problem encountered through the first 47,000 miles was high engine oil consumption, caused largely by a pinched ring in the No. 6 cylinder. However, driveability and mechanical problems were later encountered with Tractor #1, as well as with Tractors #2 and #3. These problems -- not uncommon for RD&D work in alternative-fuel engine technologies -- highlighted the need for upgrades to the S60G engine and LNG fuel systems. Such upgrades were periodically performed during the demonstration, helping to further advance commercial viability of the integrated LNG truck technology, but hindering regular use and consistent mileage accumulation.
- On an energy-equivalent basis, the three LNG tractors with upgraded S60G engines delivered about 27% lower fuel economy than the comparable S60 diesel control tractor, and 34% lower than JBK's averaged fuel economy for its fleet of Cummins M11-powered diesel tractors. Additional work is clearly needed to improve the engine efficiency and fuel economy of spark-ignited, heavy-duty natural gas engines such as the S60G. Work of this nature is already underway or planned, through other government-funded programs such as those being currently co-funded by the Commission. However, the lower measured fuel economy of the LNG tractors can be partially attributed to certain non-optimal characteristics of the demonstration. Most notably, the LNG tractors were used in a less-efficient duty cycle (local, short-haul service), and fuel-related procedures were conducive to high LNG boil off as well as excess venting losses.

### **4.2 Fuel Diversification and Emissions Benefits**

- Collectively over the course of the two related projects (February 1999 to July 2001), the three LNG tractors accumulated nearly 116,000 miles and consumed approximately 47,000 gallons of LNG. Thus, an estimated 27,500 gallons of diesel fuel were displaced. While these represent relatively small fuel quantities, the near-term potential for greater displacement of diesel fuel in California has been significantly enhanced, due to improved

commercial viability of LNG engines in the high-fuel-use Class 8 trucking sector.

- Emissions tests conducted in this program have corroborated other existing certification and chassis dynamometer emissions data, which show that LNG engines offer major NOx and PM emissions reductions compared to equivalent diesel engines. Based on emissions data from testing LNG Tractor #3 at the CaTTS laboratory, the demonstrated LNG tractors emit an estimated 50% to 80% less NOx than comparable diesel-fueled tractors. An estimated 2.5 tons of NOx emissions were avoided through the use of the LNG trucks with Series 60G engines (116,000 miles, at an average NOx reduction of approximately 20 grams per mile).
- DDC's certification of the upgraded S60G LNG engine to California's Optional Low-NOx Emissions Credit Standards at 400 hp and 1450 lbs-ft of torque is a significant (if not major) accomplishment. Strong commercial demand is anticipated for this engine, and a significant increase in deployment of heavy-duty LNG trucks may soon follow. In January 2002, the engine was finally acknowledged on the Air Resources Board website as being certified to California's optional low-NOx emission credit standards. This will enable fleets purchasing S60G-equipped heavy-duty trucks to obtain funding from the State that offsets the incremental cost of the LNG option over a comparable diesel-powered truck. The Commission-funded project described in this report played an essential role in DDC's achievement, including the recently announced eligibility of the S60G engine to receive incentive funding in California.

#### **4.3 LNG Infrastructure and Fuel-Related Technologies**

- The Ontario L/CNG station served as the primary LNG facility in the demonstration, and reliably provided LNG for the three prototype tractors. However, design flaws in the station as well as the on-board LNG fuel systems resulted in non-optimized fueling (poor fills, excessive fuel losses). Such problems constitute an unacceptable situation for commercial deployment. Towards the end of the demonstration, financial support from GTI, SCAQMD and ALT USA was used to perform a much-needed technology upgrade at the station; this paid immediate dividends towards improving the fueling of the JBK tractors, and will likely enhance the critical role the station plays as an element of the Interstate Clean Transportation Corridor (ICTC).
- The backup station used in the demonstration, Mesa Pacific's Downtown Los Angeles LNG station, received support from the SCAQMD to help keep the station operational approximately one year longer than it otherwise would have lasted. However, the station's closure in late 1999 exemplifies the fate of an alternative-fuel facility that does not have a high-fuel-use anchor fleet, even when the station seems to possess a strategic location. Throughput at such stations is so low that private-sector funding usually cannot be sustained.
- Although new LNG stations came online in California during the term of this demonstration program, accelerated expansion of the infrastructure will be needed to ensure commercial viability of LNG in Class 8 heavy-duty trucking applications. Unlike refuse haulers and transit buses, long-haul trucks do not return to the same location each night for refueling, and thus must rely of the availability of fuel en route.
- Until this classic "chicken and egg" problem is resolved, use of LNG in the Western U.S. for

Class 8 trucks is likely to be confined to the ICTC. To establish expanded corridors, it may be beneficial for trucking fleets to share LNG fueling facilities with transit districts and refuse haulers that are aggressively moving forward with LNG.

- Running out of fuel, which usually results in a road call and towing, remains a significant problem for LNG trucks. In addition to the paucity of LNG stations, the following other factors contribute to this problem: reduced vehicle range due to lower volumetric energy content of LNG; less accurate fuel gauges; a lack of extensive driver experience with LNG; the difficulty of getting cold fuel into relatively hot tanks with high vapor pressure; and the not-uncommon need to vent and service an LNG truck's onboard fuel system at a location remote from the nearest fueling station. Some of these issues require technical solutions (e.g., improved and larger on-board LNG storage tanks), while others involve institutional remedies (e.g., improved training of end users).
- Mobile LNG fuelers have been developed by companies such as ALT USA, but currently there is no readily available, practical way to fuel stranded trucks with LNG.
- On-board LNG fuel systems in the demonstration consisted of older, non-optimized equipment that significantly contributed to LNG tractor downtime and fueling problems. Promising new LNG fuel system technology is now coming to market from entities such as NexGen Fueling, a Chart Industries affiliate. However, equipment costs are still high and likely to remain so, until increased market demand stimulates volume production and encourages greater vendor competition.

#### **4.4 Other Economic and Institutional Barriers**

- For LNG to succeed as a fuel in Class 8 trucking applications, strong corporate commitments are essential from the host fleets, the fueling station providers, and the engine and chassis manufacturers. Such commitments remain an exception rather than the rule because these industries are necessarily driven by the bottom line of reducing costs and increasing profits.
- An essential element of LNG's potential for widespread application in Class 8 trucking is very high fuel consumption. This results in higher fueling station capacity utilization, which can lower fuel costs (cheaper bulk price, reduced boil off, etc.) and help to offset the added cost of LNG vehicles. JBK's small Fontana fleet had the potential to consume large volumes of fuel on a per-vehicle basis, but this did not come to full fruition due to range limitations of the LNG tractors and other factors. However, the potential to achieve large volumes of fuel use is beginning to be met in more recent LNG truck deployments, such as those at grocery chains and waste-hauler applications.
- Comprehensive training on operational and safety issues is essential and can pay for itself in the long run. It is generally necessary to perform periodic training sessions and updates, to account for the relatively high employee turnover that can occur in trucking applications.